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M. V. Yefimov

BALLISTIC MISSILE AIMING SYSTEMS

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BALLISTIC MISSILE AIMING SYSTEMS

by

M. V. Yefimov

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U. S. BOARD ON GEOGRAPHIC NAMES TRANSLITERATION SYSTEM

Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

* ye initially, after vowels, and after ъ, ь; e elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

FOLLOWING ARE THE CORRESPONDING RUSSIAN AND ENGLISH DESIGNATIONS OF THE TRIGONOMETRIC FUNCTIONS

Russian	English
sin	sin
cos	cos
tg	tan
ctg	cot
sec	sec
cosec	csc
sh	sinh
ch	cosh
th	tanh
cth	coth
sch	sech
csch	csch
arc sin	sin^{-1}
arc cos	cos^{-1}
arc tg	tan^{-1}
arc ctg	cot^{-1}
arc sec	sec^{-1}
arc cosec	csc^{-1}
arc sh	sinh^{-1}
arc ch	cosh^{-1}
arc th	tanh^{-1}
arc cth	coth^{-1}
arc sch	sech^{-1}
arc csch	csch^{-1}
rot	curl
lg	log

The Military Publishing House continues to put out the series of pamphlets "Rocket Technology," which is intended for soldiers and sergeants, students at military schools, and also for a wide circle of readers who are interested in rocket technology.

BALLISTIC MISSILE AIMING SYSTEMS

Yefimov M. V.

M. Voyenizdat, 1968. 120 p. 14,500 copies. 19 kopecks

The pamphlet "Ballistic Missile Aiming Systems" is part of the "Rocket Technology" which is put out by the Military Publishing House.

In the pamphlet in an elementary form are expounded the principles of aiming of ballistic missiles and construction of aiming systems. Basic attention in it is allotted to a consideration of the essence of aiming, the working and arrangement of elements included in the systems for aiming missiles.

The pamphlet is intended for soldiers, sergeants, students at military schools, and also for a wide circle of readers who are interested in questions of rocket technology.

The pamphlet is written with the use of materials from the open Soviet and foreign press.

A comparative appraisal of different systems and methods of aiming of missiles is given in accordance with the views of the authors of these articles.

INTRODUCTION

The flight trajectory of ballistic missiles is divided into two segments: active and passive. On the active segment the missile moves under the impact of engine thrust, forces of gravitation and drag, and also the controlling moments and forces of steering elements. On the passive segment the engine will be turned off and the missile continues free flight, being subjected only to the action of forces of gravitation and drag.

For movement of a ballistic missile on the active segment on a programmed trajectory there are special flight control systems. They are of two types: autonomous and combined. All elements of the autonomous control system are onboard the missile. The combined system includes, besides the autonomous control system, a system of radio control, some elements of which are onboard the missile, and some — on the earth.

So that the programmed trajectory of a ballistic missile passes through the target, prior to launching the body of the missile and the transducers of the autonomous control system are oriented precisely relative to vertical and for azimuth. Totality of operations during preparation of the missile for launching, ensuring the spatial orientation of the body of the missile and the transducers of the control system, is called aiming the missile.

In the process of aiming the missile various operations are fulfilled. These are connected with determination of azimuths of directions, measurement of angles, remote transmission of angular values, and exact turning of the missile and the transducers of its control system on definite angles. These operations are fulfilled with the help of devices and instruments, the action of which is based on various physical principles. Thus, during aiming optical, photoelectric, gyroscopic, electronic, and electromechanical instruments are used. All these instruments and devices are united in a single semiautomatic or automatic system, fulfilling all the basic operations of aiming – an aiming system.

The construction of aiming systems and arrangement of distribution of their elements on the launching site are changed essentially depending the designs of the missiles, type of control systems, and type of launchers. Some of the elements of the aiming system are mounted onboard the missile on its protective container, and on the launching pad, and certain elements of the system are located on the earth, sometimes at considerable distance from the missile.

Ballistic missiles with autonomous control systems are characterized by a high degree of accuracy of hitting the target. At flight ranges of 10,000-12,000 km the impact points of nose cones of rockets deviate from the target all told by several kilometers. This is attained not only due to a perfected control system, but also due to a high degree of accuracy of aiming.

During the development of such high-precision aiming systems it is necessary to surmount considerable fundamental and constructive difficulties. Especially great difficulties appear in the development of aiming systems which provide for the launching of ballistic missiles from moving bases (submarines, railroad flatcars, etc.). During launching of missiles under such conditions the determination of azimuths of initial directions for aiming is hampered. Furthermore, the rolling of a submarine causes the appearance of additional errors in the aiming of missiles.

At present there is practically an absence of literature, where questions of aiming of ballistic missiles are examined sufficiently fully. Information about the aiming of missiles, circuits of aiming system, and their principles of action are expounded in a number of articles, published in American journals, and also in certain Soviet works, dedicated to the various problems of rocket technology.

In this pamphlet a generalization of this information is made. Basic attention in it is allotted to a popular account of principles of aiming of missiles and physical bases of operation of aiming systems and their elements.

CHAPTER I

GENERAL INFORMATION ON MISSILE AIMING

§ 1. Systems of Coordinates Utilized During Aiming

Orientation of the body of a missile and transducers of the control system during aiming is carried out relative to a starting system of coordinates $OX_cY_cZ_c$, which is depicted in Fig. 1. This system of coordinates is clockwise. Its origin coincides with the center of mass of the missile mounted on the launching pad. Axis OY_c is directed vertically upwards, and axes OX_c and OZ_c lie in a horizontal plane. Axis OX_c indicates direction of firing and its position is determined by azimuth of launching $A_И$.

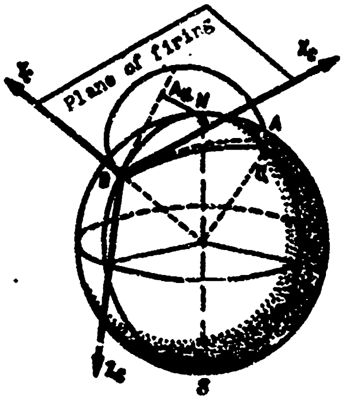


Fig. 1. Starting system of coordinates.

The vertical plane Y_cOX_c tangent to the programmed trajectory of movement of the missile at the location of the launching pad, is called the plane of firing or launching. Due to rotation of the earth and several other factors the trajectory of movement of a missile is a line of double curvature, therefore it does not coincide with the plane of firing and is deviated from it in the northern hemisphere to the right, and in the southern – to the left.

Rigidly bound with the body of missile is the connected system of coordinates $OX_1Y_1Z_1$ which is depicted in Fig. 2. Its origin is placed in the center of mass of the missile. Axis OX_1 coincides with the longitudinal axis of the missile, the direction of remaining axes is determined by the location of the steering elements. A plane, passing through the longitudinal axis of the missile and steering motors I-III, is called the basic plane of symmetry.

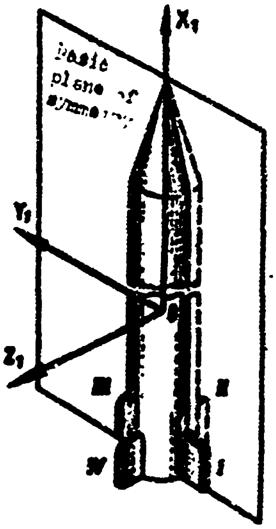


Fig. 2. Connected system of coordinates.

Direction of axes of sensitivity of gyroscopic and inertial transducers of an autonomous control system determines the inertial system of coordinates.

Autonomous control systems are of two varieties. In the first of them angular stabilization of the missile is carried out with the use of free gyroscopes as transducers (Fig. 3). A roll stabilizer develops commands, controlling the position of the missile on axes of yaw OX and roll OY of the inertial system of coordinates. A gyro-horizon produces the controlling command for the axis of pitch OZ.

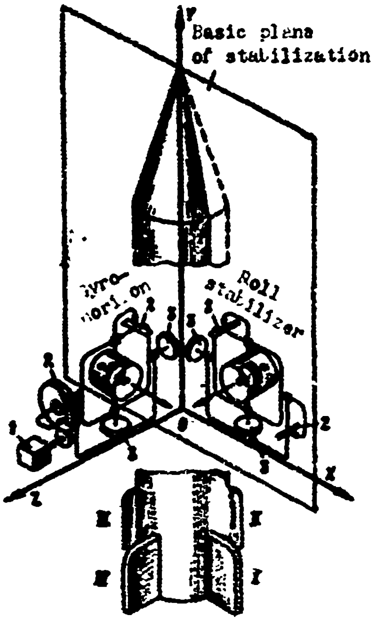


Fig. 3. Inertial system of coordinates: 1 - program unit; 2 - angle transducer; 3 - moment transducer.

The plane YOX is called the basic plane of stabilization of the missile. Axis of rotation of the rotor of the roll stabilizer is perpendicular to this plane, and the axis of rotation of the rotor of the gyro-horizon lies in it. In the basic plane of stabilization the programmed turn of the missile for angle of pitch takes place.

In the second variety of autonomous control systems its basic transducers are located on a stabilized platform, preserving during the entire controlled period of flight of the missile a constant position relative to the fixed system of coordinates. For stabilization of the platform here three gyroscopes are used: for pitch, yaw and roll. Position of the gyroscopic and intertial transducers (accelerometers), which are mounted on the gyro-stabilized platform, relative to the inertial system of coordinates is depicted in Fig. 4. Axes of the inertial system of coordinates here are determined by the axes of suspension of the platform, and the basic plane of stabilization coincides with the plane of the inner frame of the platform.

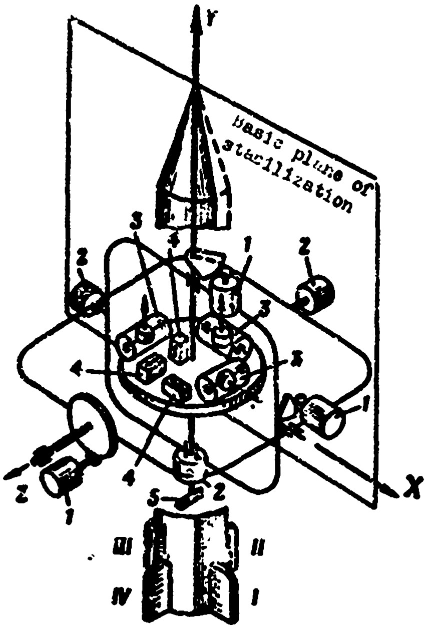


Fig. 4. Inertial system of coordinates: 1 – motor for stabilization; 2 – angle transducer; 3 – gyroscope; 4 – accelerometer; 5 – control prism.

Orientation of the stabilized section of the gyroplatform relative to its fixed base prior to launching of the missile is done with the help of a three-channel system of azimuthal and horizontal reduction. Sensing elements of the system of horizontal reduction are the accelerometers, and of the system of azimuthal reduction – angle of roll sensor mounted on axis OY.

The system of reduction ensures retention of the platform in the required position after its locking right up to the moment of launching of the missile. Before launching the system of reduction of the gyroplatform is switched on and the three-channel system of stabilization begins to operate.

§ 2. Essence of Aiming

By the moment of launching of a missile the axes of connected and inertial systems of coordinates are oriented in a specific way relative to the axes of the starting system of coordinates. This orientation is carried out in the process of aiming the missile.

The final position of the axes of all three systems of coordinates prior to launching of the missile should be the following: basic planes of stabilization and symmetry of the missile are combined with the plane of firing, and the longitudinal axis of the missile and axis OY of the inertial system of coordinates are vertical.

The cited position of axes of systems of coordinates is attained in four stages:

- setting the missile vertical;
- azimuthal aiming;
- adjustment of gyroplatform;
- setting the gyroplatform horizontal

Setting the missile vertical is the name given to the totality of operations for imparting to its longitudinal axis a vertical position on the launching pad. This operation is carried out directly after installation of the missile on the launching pad.

Azimuthal aiming is the name given to actions for combination of the basic plane of stabilization of the missile with the plane of firing. It is carried out by two methods. The first method amounts to the fact that the missile together with the gyroinstruments mounted onboard is turned around a vertical axis to coincidence of the basic plane of stabilization with the plane of firing. This turning is done with the help of the turning mechanism of the launching pad. The second method consists of the separate combination with the plane of firing of first the basic plane of symmetry, and then the basic plane of stabilization of the missile. Coarse combination of basic plane of symmetry with plane of firing is carried out by means of turning the missile and exact azimuthal aiming is done by turning the gyroplatform on an azimuth relative to the body of the missile.

Adjustment of gyroplatform has as its goal the combination of basic plane of stabilization with the basic plane of symmetry of the missile following switching on of the system of azimuthal reduction of the gyroplatform. Adjustment of the platform is fulfilled by turning its base relative to the body of the missile after installation of the gyroplatform onboard the missile.

Setting the gyroplatform horizontal consists of combining the axis OY of the inertial system of coordinates with the vertical axis of the starting system of coordinates. This operation is carried out automatically. Accelerometers mounted on the platform are used as transducers for producing mismatch signals in the event of deviation of plane of the gyroplatform from the horizontal. Signals from accelerometers are fed to drives for making the platform horizontal.

§ 3. Initial Data for Aiming

In order to fix direction of firing directly at the launching site, before aiming of the missile two preparatory operations are fulfilled:

- geodetic preparation for launching;

- preparation of initial data for firing.

During geodetic preparation for launching the coordinates of the location of launching pad and oriented directions for the launching site are determined. Coordinates of the location of the launching pad together with target position data are used during the preparation of initial data for firing, and oriented geodetic directions are used directly for azimuthal aiming of the rocket.

Orientation of directions consists of the determination of geodetic azimuth of direction of some straight line which is taken as the oriented line. It can be done by three methods:

- from a geodetic grid;

- from astronomical observations;

- with the help of gyroscopic instruments.

Orientation of directions from a geodetic grid is done by methods of triangulation or laying off of angular courses. As initial points for orientation of directions only points are used from geodetic grids of those classes, for which errors of orientation of the sides are considerably less than the permissible errors for geodetic preparation for launching.

Astronomical orientation is used when in the region of the launching sites there is an absence of a well-developed geodetic grid, for satisfying the requirements of accuracy for geodetic preparation. Astronomical orientation is characterized by a high degree of accuracy, however, its application is possible only during favorable meteorological conditions.

Orientation with help of gyroscopic devices is used in the absence of preliminary geodetic preparation of the launching site. For orientation of directions it is possible to use external gyroscopic devices which are placed at a specific distance from the launching pad, and onboard gyroscopes of the missile autonomous control system which are working under conditions of determination of azimuth of oriented direction.

Thus, during aiming of a missile it is possible to use external information if the oriented directions are determined from a geodetic grid, from astronomical observations, or with help of external gyroscopic devices. This method of aiming is more accurate and has received the widest distribution. The second method of aiming is based on the use, for determination of oriented geodetic direction, of information produced by onboard gyroscopic instruments.

During aiming of the missile oriented geodetic directions are fixed by using external information at the launching site ahead of time. Fixing is carried out by one of two methods: the use of oriented points, fixed on the terrain by signs, or with the help of collimators.

In the first case as the oriented direction a straight line passing through any two points of terrain is used. Error of orientation ΔA here depends on accuracy of setting up the theodolite on one of these points and length of oriented base

$$\Delta A = \frac{\Delta l}{L}, \tag{1}$$

where Δl – circular error of setting up the theodolite; L – length of oriented base.

Value of error of orientation here is expressed in radians.

In the second case the oriented direction is fixed by a collimator – a special optical instrument, converting the rays of a light source into a pencil of parallel rays (Fig. 5). The collimator consists of objective and a certain illuminated sign placed in its focal plane. Such a sign may be, for example, cross hairs of filaments on a light background or a luminescent narrow opening in an opaque diaphragm. The oriented direction here is the sighting axis – a line passing through the center of the objective of the collimator and the cross hairs of its grid. In order to orient the theodolite with a collimator it is necessary to set it in a parallel pencil of rays emanating from the collimator. When the cross hairs on the grids of the theodolite and collimator coincide their sighting axes will be parallel.

In the process of preparation of initial data for firing, data are determined which are utilized in adjusting the control system, and the firing azimuth, which is utilized for aiming the missile.

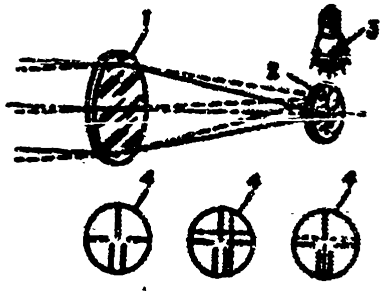


Fig. 5. Collimator: 1 – objective; 2 – grid; 3 – lamp; 4 – appearance of field of vision.

§ 4. Control Elements Utilized During Aiming

For aiming the missile it is necessary to fix not only the position of the plane of firing, but also the position of the basic plane of stabilization. The basic plane of stabilization is usually fixed with the help of two types of elements: mirrors and mirror prisms.

These elements are attached to the stabilized platform when it is manufactured (see Fig. 4) and are oriented with great accuracy relative to the basic plane of stabilization of the missile. In certain types of ballistic missiles control elements are also fastened to the turning section of the launching pad.

A more widespread control element is the rectangular mirror prism depicted in Fig. 6. A peculiarity of its working is the fact that a light ray, falling on the hypotenuse face of the prism in a certain plane P, emerges from it conversely in plane Q, parallel to plane P. Moreover in points a and d the ray is refracted on the hypotenuse face of the prism, and in points b and c it is reflected from its silvered leg faces. Thanks to this property of the prism it is not necessary that it be set exactly vertical in plane YOX, since even if the incoming ray does not lie in plane XOZ, the reflected ray will go in the opposite direction in a plane parallel to the plane of its incidence.

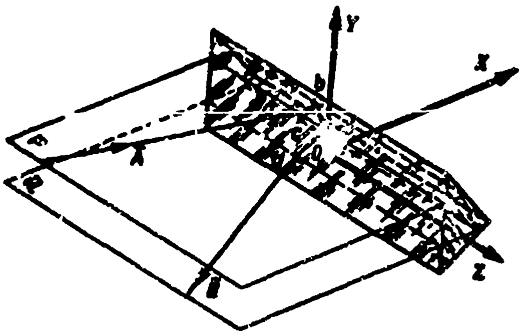


Fig. 6. Rectangular prism.

If the angle of mismatch, measured by the theodolite, between its sighting axis and a perpendicular to the edge of the right angle of the prism does not equal zero, the angle between incident and reflected rays is equal to a doubled angle of mismatch. If, however, the angle of mismatch equals zero, the incident and reflected rays are parallel to each other.

Determination of the azimuthal position of control elements is done by using the principle of autocollimation. Autocollimation is the name given to a movement of light rays, at which they emerge from the instrument in a parallel bundle and, being reflected from a mirror surface, pass through elements of the instrument in the opposite direction. The principle of autocollimation is illustrated in Fig. 7: if the surface of the mirror is perpendicular to the sighting axis of the autocollimator, the straight and the autocollimating image of its grid coincide with each other.

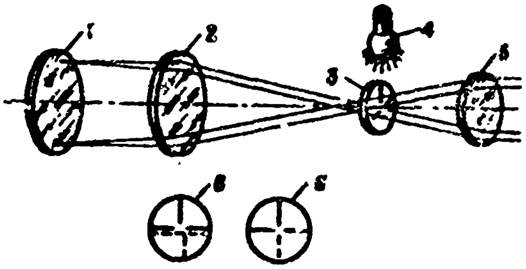


Fig. 7. Autocollimator: 1 – mirror; 2 – objective; 3 – grid; 4 – lamp; 5 – eyepiece; 6 – appearance of field of vision.

By using the principle of autocollimation, it is also possible to resolve the reverse problem: to set the control mirror or prism of the gyrostabilized platform on an assigned azimuth. For this it is turned relative to the vertical axis and, while observing in the autocollimator, an attempt is made to superpose the direct and autocollimating images of its grid.

§ 5. Influence of Errors of Aiming on Deviation of Points of Impact of Missiles

If there is an error in an azimuthal aiming the plane of firing is deviated from calculated by an angle equal to the angular error of aiming. Therefore, the trajectory of the missile will also deviate from calculated trajectory, and point of impact of the nose cone of the ballistic missile will not coincide with the target.

For determination of the relationship between error of aiming and deviation of the point of impact of the missile from the target we will use Fig. 8, in which projections of calculated and real trajectories of a missile on the surface of the earth are depicted.

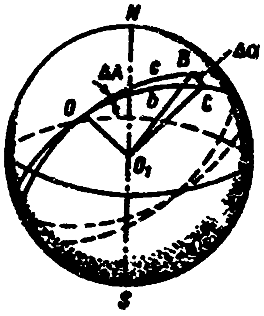


Fig. 8. Deviation of point of impact of missile.

On the basis of the theorem of cosines the relationship between elements of oblique spherical triangle OBC is expressed by the following dependence

$$\Delta a = \cos b \cdot \cos c + \sin b \cdot \sin c \cdot \cos \Delta A, \qquad (2)$$

where b, c – spherical flight ranges of missile; Δa – spherical deviation of point of impact of missile from target; ΔA – error of azimuthal aiming.

Considering in this dependence b = c, we obtain

$$\cos \Delta a = \cos^2 b + \sin^2 b \cdot \cos \Delta A,$$

from which after certain conversions we have

$$\sin \frac{\Delta a}{2} = \sin b \cdot \sin \frac{\Delta A}{2}. \qquad (3)$$

It follows from the expression obtained that deviation of point of impact of the missile from the target at a constant error of aiming is maximum at spherical flight ranges $b=\frac{\pi}{2}$ and $b=\frac{3\pi}{2}$, i.e., at linear flight ranges equal to 10,000 km and 30,000 km. Calculations by formula (3) show that with such flight ranges an angular error of aiming equal to 1', corresponds to a deviation of point of impact of the missile equal to 1.85 km.

If, however, the spherical flight ranges of the missile $b=\pi$ and $b=2\pi$, then at any value of error of azimuthal aiming there will be no deviation of point of impact of the missile, from the target.

We will examine the influence of errors of vertical mounting on the accuracy of azimuthal aiming of missiles. For this let us turn to Fig. 9, which illustrates the autocollimating principle of aiming. At point A an autocollimator is set up which directs a pencil of parallel rays on a prism which is mounted onboard the rocket.

If the edge of the right angle of the prism is parallel to axis OZ_c, ray O_1B, which is reflected from the prism, coincides with incident ray AO_1. Slopes of the prism in plane YO_1X do not cause a change of direction of the reflected ray, however, rotation of the prism around axes O_1Y and O_1X leads to a deflection of reflected ray from incident.

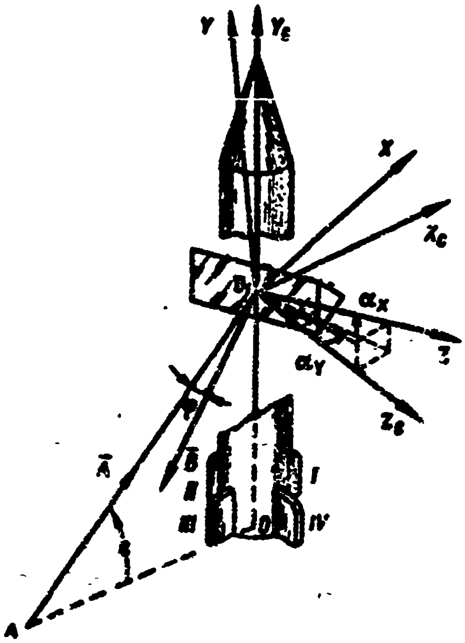


Fig. 9. Autocollimating principle of aiming.

Using the known laws of reflection of light rays from mirror surfaces, the following formula can be obtained

$$\Delta\alpha_y = \mathrm{tg}\,\varepsilon \frac{\cos\alpha_x}{\cos\alpha_y}\Delta\alpha_x, \qquad (4)$$

where α_x and α_y – angles of deflection of prism from axis OZ in vertical and azimuthal planes; ε – angle of site of prism; $\Delta\alpha_x$ – error of vertical mounting; $\Delta\alpha_y$ – error of azimuthal aiming. This dependence is presented in Table 1. In order to decrease the influence of errors of vertical mounting on the accuracy of azimuthal aiming, it is necessary to decrease the angle of site ε. Therefore, during aiming of missiles under conditions of launching from ground launchers the autocollimator is set up at a sufficiently great (up to 300 m) distance from the launcher.

During launching of missiles from site launchers the autocollimator is set on the same height as the gyroplatform, consequently the angle of site of the sighting axis of the autocollimator is close to zero. Under these conditions even considerable errors in the vertical mounting of a missile have practically no influence on the accuracy of azimuthal aiming.

Table 1.

$\Delta\alpha_x$	ε			
	1′	20′	1°	5°
1′	0″,02	0″,35	1″,0	5″,2
5′	0″,09	1″,74	5″,2	26″,1
10′	0″,17	3″,48	10″,4	52″,2

§ 6. Missions Solved by Aiming Systems

Aiming of ballistic missiles is accomplished with the help of turning and erection devices on the launching pad, turning devices of the gyrostabilized platform, and the aiming system. With the help of the erection device of the launching pad the missile is mounted vertically and with the help of a turning device azimuthal aiming is performed.

During preparation for aiming, and also when carrying it out, at the starting position it is necessary to perform a large number of various operations connected with determination and fixing of directions, measurement of angles, and turning of aiming instruments, gyroplatform, and body of the missile on specific angles.

Operations for vertical mounting of a missile are comparatively simple. They amount to determination of angles of deflection of longitudinal axis of the missile from vertical and to setting up of the body of the missile in a vertical position.

More complex problems have to be solved during azimuthal aiming. The basic ones are:

- determination of azimuths of oriented directions;
- fixing of oriented directions on the terrain;
- fixing of basic plane of stabilization of the missile;

- transmission of oriented directions from one instrument to another;

- measurement of horizontal angles;

- turning of instruments on specific angles;

- turning of gyroplatform and missile up to coincidence of basic plane of stabilization with plane of firing.

The first three problems are solved ahead of time; the last ones are fulfilled directly during preparation of the missile for launching. For the purpose of decreasing the time for aiming of a missile and increasing the accuracy of aiming, automatic aiming systems are usually used.

§ 7. Classification of Aiming Devices

Depending on the the purpose of devices included in aiming systems, they are divided into the following groups:

- instruments for determination of azimuths of oriented directions;

- instruments for fixing oriented directions;

- instruments for vertical mounting of missile;

- instruments for azimuthal aiming.

Based on physical principles, lying at the basis of operation of aiming devices, they are broken down in the following way:

- optical-mechanical;

- photoelectric;

electronic;

- electromechanical;

- gyroscopic.

An example of optical-mechanical instruments with visual reading of angles are theodolites. They are used extensively in the determination of azimuths of oriented directions and in the vertical mounting of missiles.

In photoelectric instruments information concerning the measured angle of mismatch is initially carried by a light signal, which then will be converted into electrical. A peculiarity of photoelectric instruments is the high degree of accuracy of measurement of angles.

Electronic devices are used in aiming systems for processing, amplification, and conversion of signals.

Electromechanical devices find wide application in aiming systems. They are used for measurement of angles, remote transmission of them, and adjustment of angular mismatch.

Gyroscopic devices are used for determination of azimuths of oriented directions. An example of such a device is the gyrocompass.

C H A P T E R II

PHOTOELECTRIC DEVICES

§ 1. Assignment and Classification

Photoelectric devices serve for solving the following problems:

- automatic measurement of small angles of mismatch between basic plane of stabilization of missile and plane of firing;

- output of electrical signals, depending on measured angular mismatch;

- transmission of oriented directions in a vertical plane;

- measurement of azimuthal angles in the large range of their change.

Depending on problems being solved, photoelectric devices are divided into three groups:

- goniometers;

- synchronous gears;

- angle transducers.

[illegible] [illegible] solve the first two problems. They are [illegible] with [illegible] external source of light signal and with an internal source (autocollimating). A goniometer includes the following elements: source of radiation, optical system, receiver of radiation, amplifier, and signal converter. The light signal, generated in the source of radiation, falls on a control prism mounted onboard the missile, and, being reflected from it, is received and analyzed by the goniometer.

Goniometers can work in two regimens: zero and measuring. Under zero operating conditions the mismatch signal produced by the gomiometer is fed to the drive of the gyroplatform or drive of the turning mechanism for the launching pad. With this the gyroplatform or missile is turned up until coincidence of the basic plane of stabilization with the plane of firing. During measuring operating conditions the goniometer measures angle of mismatch and produces an electrical signal which is proportional to the measured angle. The electrical signal can be produced by the goniometer in a pulse or continuous form.

In the process of aiming a missile it is necessary to carry out transmission of oriented directions in a vertical plane: from the level of the launching pad upwards to the instrument section of the missile or from the surface of the earth downwards into a silo launcher. Such a transfer of azimuthal directions is done with the help of photoelectric synchronous gears.

Photoelectric angular transducers serve for measurement of large angles of turn for various instruments and devices. Range of change of angles here can reach 360°.

§ 2. Elements of Photoelectric Devices

Gas-discharge tubes and filament tubes are used as sources of light signals in photoelectric devices. Power of light radiated by a filament tube depends on power of current consumed by it and temperature of the [illegible] of incandescence which is made from tungsten

During passage of a light signal in the atmosphere it is weakened due to its absorption and scattering on solid and liquid particles (dust, smoke, snow, rain, fog). Its weakening is determined by the following formula

$$\Phi=\Phi_0 e^{-\beta L}, \qquad (5)$$

where Φ_0 – initial value of luminous flux in lumens; Φ – value of luminous flux after its passage through a certain layer of atmosphere with thickness L; β – attenuation factor of luminous flux on thickness of layer L = 1 km. Value of attenuation factor of light depending on atmospheric conditions is given in Table 2. Calculation by formula (5) shows that with a moderate fog in a thickness of layer of atmosphere L = 100 m up to 90% of the luminous flux is absorbed and scattered. It follows from this that the performance of photoelectric goniometers depends essentially on weather conditions.

Table 2.

Atmospheric condition	Dense fog	Moderate fog	Mist	Dust haze	Clear
β	85.6	21.4	8.54	2.14	0.43

Optical systems of instruments serve for solving the following problems:

– creation of parallel pencils of light radiated by the instrument;

– focusing of light rays;

– separation, connection, and change of direction of light rays. The magnitude of light signal received by the instrument is proportional to the area of its objective.

For conversion of light signals into electrical photoelectric radiation receivers are used. Their action is based on two varieties of photoeffect: external and internal. From receivers with photoemission, under the impact of quanta of light falling on their surface free electrons break loose. Under the impact of potential difference, applied to electrodes of the receiver, an electrical current emerges. In receivers with photoconductive effect the electrons liberated by quanta of light remain in substance and increase its conductivity.

The basic characteristic of receivers of radiation is their sensitivity - ratio of passing current to magnitude of light flux

$$\kappa=\frac{I}{\Phi}. \qquad (6)$$

The greater the sensitivity of the receiver, the greater the signal on its outlet at a constant value of light signal.

A receiver of radiation with photoemission constitutes glass cylinder in which a high vacuum is created. On one of its walls a layer of photosensitive material is applied - silver oxide with an admixture of cesium, which forms the cathode. In the center of the cylinder an anode is set up. Between the anode and cathode a potential difference of up to 400 V is applied. During irradiation of the cathode by light flux the current which is flowing between the anode and cathode increases. The magnitude of passing photocurrent depends on applied potential difference and value of incident luminous flux. Sensitivity of receivers with photoemission comprises 50-100 μA/lm.

A higher sensitivity up to 100 A/lm is possessed by photomultipliers. In the cylinder of a photomultiplier a photocathode, emitters, and anode are mounted. Between the cathode and the first emitter, and also between each of the neighboring emitters a positive voltage is applied. When electrons are dislodged from the surface of the photocathode they rush to the first emitter with a speed which is sufficient for dislodging secondary electrons. Here the quantity of secondary electrons is considerably greater than the quantity of primary electrons. Thanks to this the current on the anode is approximately 10^6 times greater than the current on the photocathode.

An example of a receiver of radiation with a photoconductive effect is a photoresistor. It constitutes a layer of semiconductor coated on a glass base layer. For inclusion of photoresistance on the input of the amplifier it has two electrodes. When light falls on the photoresistor its conductivity is increased, and photocurrent flowing through the photoresistor also increases. Sensitivity of photoresistors reaches 0.02 A/lm.

Valve photoelectric receivers also are based on the use of the photoconductive effect. A valve receiver consists of a metallic plate, a layer of metal oxide, and a metallic grid. Between the oxide and metallic plate a layer will be formed which possesses the ability to conduct current only in one direction – from the metal to the oxide. Free electrons, liberated during illumination of the layer, penetrate the metal. If the electrodes of the receiver are locked on the external circuit, the electromotive force developing in the receiver causes the appearance of a current. Thus valve receivers do not require an external voltage supply.

Photodiodes are prepared from two plates of semiconductor with different type of conductivity. In the event of illumination of the boundary of division of these plates an electromotive force emerges in the photodiode. Photodiodes possess a very high sensitivity; it reaches 0.02 A/lm. A still higher sensitivity (up to 0.5 A/lm) is possessed by phototriodes. They possess the ability to strengthen the electromotive force developing in them.

§ 3. Goniometer with External Light Source

A diagram of a goniometer with an external light source is shown in Fig. 10. Its basic units are: light source, tube, scale section, and base. In the goniometer tube which is attached to the turning portion of the goniometer, an optical system and receivers of radiation are located. Basic elements of the scale section are the scale and reading device. With the help of the reading device angles of rotation of the goniometer are counted off with a scale division value to fractions of a second. The scale section is disposed on the base, which has two rectilinear guides. With help of an automatic drive the scale section can be displaced forward on the guides.

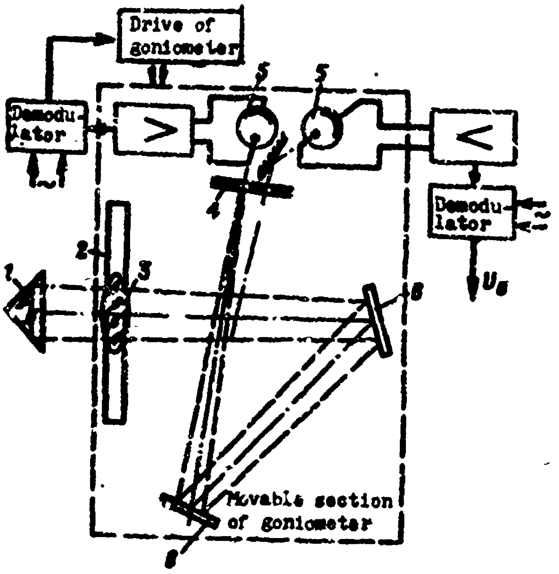


Fig. 10. Goniometer with external light source: 1 - control prism; 2 - tube; 3 - objective; 4 - diaphragm; 5 - receiver of radiation; 6 - mirror.

As sources of light signal in goniometer two gas-discharge tubes are used, one of which is secured over the objective, and the other - under it. A vertical plane, passing through the center of the objective of the goniometer, is the boundary between the tubes.

The tubes are powered by rectified alternating voltage; on one of them a positive half-wave of voltage is supplied, and on the second - negative. Thus, phases ψ of light signals on the outlet of tubes are shifted relative to one another by 180°.

For increasing accuracy in the goniometer a long-focus objective with a focal length of 500 mm is used. In order to decrease the dimensions of the goniometer tube mirrors which change the direction of movement of rays are used in the optical system.

Images of tubes, reflected from the onboard control prism, are constructed with the optical system in the focal plane where the diaphragm is mounted. The diaphragm is a flat mirror with two slots with a width of 0.005 mm. These images have the appearance shown on the right in Fig. 11. A line connecting the center of the objective and center of the slot is the sighting axis of the goniometer.

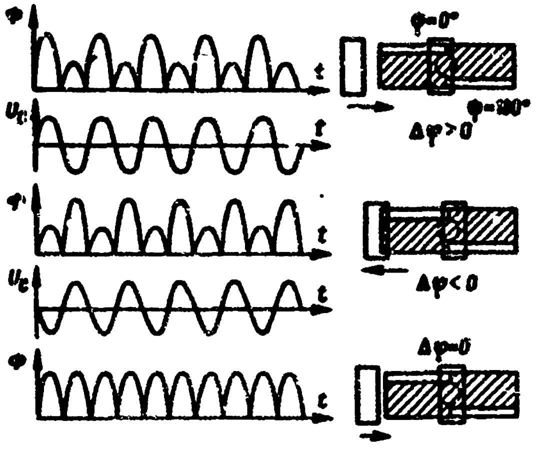


Fig. 11. Diagrams of signals.

If the edge of the right angle of the control prism is perpendicular to the sighting axis of the goniometer, then the right slot coincides with the boundary between images of the tubes. If this condition is not observed the slot will not coincide with the boundary between images of the tubes. Through this slot a luminous flux will fall on the photoelectric receiver. This flux is participating in the output of mismatch signal which is passed onto the drive of the gyroscopic platform.

Principle of action of the goniometer is illustrated by the signal diagrams depicted on the left in Fig. 11. If the angle of mismatch measured by the goniometer $\Delta\phi > 0$, then the share of luminous flux incident through the slot onto the receiver from the first tube will be greater than from the second. The envelope harmonic of light signal here will have a zero phase. In case, when measured angle $\Delta\phi > 0$, light signal from the second tube will be greater, therefore the envelope harmonic of the signal changes phase by 180°. On the output of the goniometer mismatch signal will be converted to a constant (U_B). Its polarity depends on sign of measured angle of mismatch, and amplitude - on value of angle.

If the missile is aimed correctly, the sighting axis of the goniometer is perpendicular to the edge of the right angle of the control prism and the measured angle of mismatch $\Delta\phi = 0$. Components of light signal from both tubes will be equal, and their envelope has a frequency twice as large as the frequency of modulation of light. The signal of doubled frequency is suppressed in amplifying duct of the goniometer, therefore on its outlet mismatch signal U_B is equal to zero.

Through the left slot on the radiation receiver a luminous flux falls which participates in the output of a mismatch signal controlling the forward shift on the goniometer on the guides. The action of this servosystem ensures the continuous goniometer tracking of shifting of the control prism due to wind rolling of the missile. This excludes possibility of loss by the goniometer of the light signal reflected from control prism at high amplitudes of oscillations of the missile.

The principle of separation of the controlling signal amounts to the following. If a luminous flux does not pass through the left slot the mismatch signal on the output of the demodulator of the goniometer ensures forward shift of the goniometer to the right (shown by arrow). If the luminous flux of any phase passes through the slot, the signal ensures forward shift of the goniometer to the left. Thus the middle position of the left slot corresponds to the left edge of the control prism.

§ 4. Autocollimating Goniometers

We will examine the principle of operation of an autocollimating goniometer working under measuring conditions (Fig. 12).

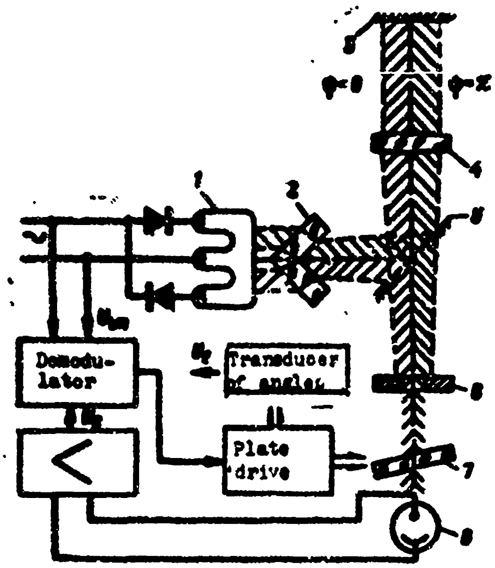


Fig. 12. Goniometer with two-phase tube: 1 – tube; 2 – distributing prism; 3 – mirror; 4 – objective; 5 – semitransparent mirror; 6 – diaphragm; 7 – plate; 8 – receiver of radiation.

Source of radiation in the goniometer is a two-phase mercury tube, which is powered by voltage rectified with the help of diodes. Since diodes are included in the power circuit of each of the arms of the tube by a different method, then each of the halves of the tube will be lighted in turn through half of a period. Consequently, the phases of luminous fluxes radiated by the halves of a tube will be shifted relative to one another by 180°.

Luminous fluxes from both parts of the tube enter a distributing prism, where they are shifted toward each other. Here the luminous flux radiated by the central part of the tube is reflected aside by the distributing prism and does not participate in the creation of the signal. Thanks to this on exit from the prism the boundary of luminous fluxes of different phases is sufficiently sharp.

Both parts of the luminous flux are reflected from the semitransparent mirror and in the form of two adjacent parallel bundles emerge from the objective. Light rays reflected from the control prism which fixes the basic plane of stabilization of the missile enter the objective of the goniometer and are focused by it in the plane of the diaphragm with the slot.

For an illustration of the principle of operation of a goniometer it is possible to use the signal diagrams, depicted in Fig. 11. If the edge of the right angle of the prism is perpendicular to the sighting axis of the goniometer, then through the slot luminous fluxes fall on the receiver of radiation which are of both phases and equal in amplitude. The mismatch signal, produced by the demodulator of the goniometer, is equal to zero in this case. If however, between the sighting axis of the goniometer and a perpendicular to the edge of the control prism there is a certain angle $\Delta\phi$, different from zero, the amplitudes of luminous fluxes falling on the receiver of radiation are not equal to each other. The envelope phase of the light signal depends on the sign of the mismatch angle. On the output of the demodulator of the goniometer a constant controlling signal will be produced, the polarity of which corresponds to the sign of measured angle, and the amplitude to its value.

After amplification the controlling signal moves to the drive for turning the plane-parallel plate. With its turning around a vertical axis perpendicular to the sighting axis of the goniometer, the light bundles passing through the plate are displaced. The motor turns the plate until the boundary of luminous fluxes of different phases are combined with the middle of the slot.

Based on the value of the angle of rotation of the plane-parallel plate it is possible to judge the initial value of the angle between the sighting axis of the goniometer and a perpendicular to the control prism. Measurement of angles with the goniometer is carried out with a high degree of accuracy: with a width of slot in the diaphragm equal to 0.001 mm the maximum error of measurement of angle comprises 0.1".

For measurement of large horizontal and vertical angles the goniometer has horizontal and vertical scales. In goniometer an objective with a large diameter is used, therefore in the case of wind rolling of the missile the reflected beam of light rays does not go beyond its limits. Due to this in the goniometer there is no servosystem ensuring its forward shift behind the control prism during wind rolling.

In the examined autocollimating goniometer the source of light signal is established in the focal plane of the objective, therefore its accuracy practically does not depend on the distance to the control prism. It is most expedient to use such goniometers for aiming of missiles in the event of launching them from silo installations.

In Fig. 13 is shown a diagram of an autocollimating goniometer working under zero conditions. As source of light signal in the goniometer two filament tubes are used which are powered by alternating voltage. On one of the tubes a positive half-wave of voltage is fed, and on the other - negative, therefore the light signals radiated by the tubes are in opposition.

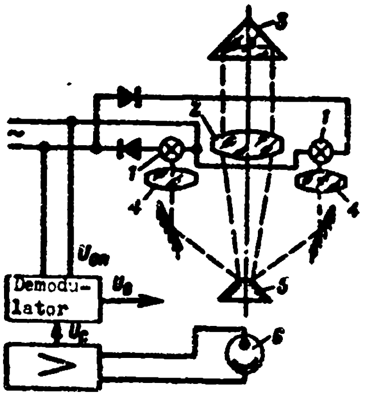


Fig. 13. Goniometer with filament tubes: 1 - tube; 2 - objective; 3 - control prism; 4 - condenser; 5 - analyzing prism; 6 - receiver of radiation.

With the help of condensers light rays from the tubes are focused on the mirror faces of the analyzing prism. After reflection from the prism the light rays pass through the objective and emerge from it in a parallel bundle. The objective of such a goniometer has a diameter up to 100 mm and a focal length up to 900 mm. A large diameter of objective ensures the great range of the goniometer, and the long focal length - its high accuracy.

If the sighting axis of the goniometer is perpendicular to the edge of the control prism, the luminous flux reflected from it is focused by the objective on the middle of the analyzing prism. The vertex of the edge of the prism is cut and polished, therefore through this cut two luminous fluxes of opposite phases, but having equal amplitudes, fall on the receiver of radiation. The controlling signal, produced by the goniometer and passed on to the drive of the gyroplatform, in this case equals zero.

In the case when the sighting axis of the goniometer is perpendicular to the control prism, the amplitudes of luminous fluxes of different phases, incident through the cut of analyzing prism, will be unequal. On the output of the goniometer here a controlling signal will be produced which is different from zero. For production of a controlling signal there is a phase demodulator, to which, besides the signal from the receiver of radiation, a support signal having the same frequency, but a constant phase is fed.

Let us consider the arrangement of the autocollimating goniometer, working under zero conditions, during aiming of the American space missile "Saturn" (Fig. 14). It includes an autocollimating tube and tracking mirror reflector. The tracking mirror reflector is displaced on the guides after wind rolling of the instrument section of the missile. Range of the goniometer is 300 m, and accuracy of measurement of angles is characterized by an error which does not exceed 2".

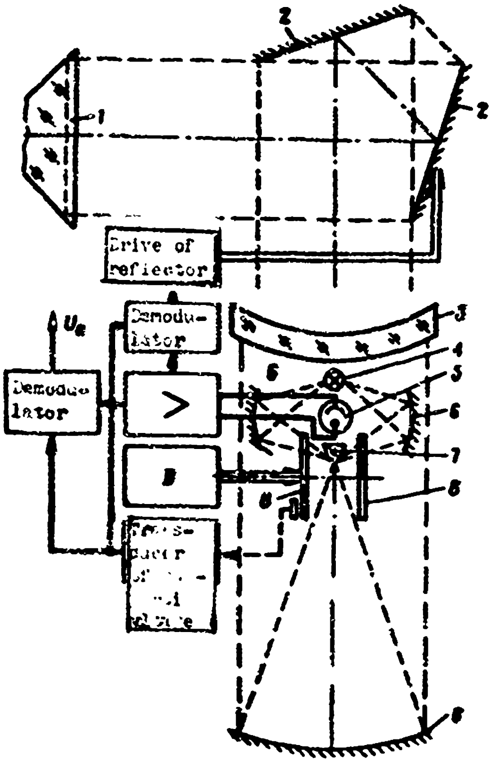


Fig. 14. Goniometer with mechanical modulation of signal: 1 – control prism; 2 – mirror reflector; 3 – lens; 4 – tube; 5 – receiver of radiation; 6 – mirror; 7 – analyzing prism; 8 – modulator.

As the source of light signal in the goniometer a filament tube powered by direct current is used. In the goniometer a complex mirror-lens objective is used; its diameter equals 203 mm, and focal length - 760 mm.

With the help of two focusing reflectors the luminous flux is converged on the mirror faces of the analyzing prism. On the path of each part of the luminous flux modulating disks are set, thus ensuring their modulation in a reversed phase with a frequency of 226 Hz. From the faces of the analyzing prism the luminous flux is directed onto the mirror of the objective and, being reflected from it, emerges in a parallel bundle from the lens.

The parallel beam is turned 90° by the reflector and directed to the control prism which is secured on the gyro stabilized platform. The angle between planes of mirrors of the tracking reflector is 45°, therefore regardless of error in its orientation relative to the sighting axis of the goniometer, the beam is turned precisely by 90°. Thus the error of aiming does not depend on nonrectilinearity of the guides on which the tracking reflector shifts.

Light rays reflected from the control prism are again focused on the analyzing prism and through its polished cut on the vertex reach the receiver of radiation. As the receiver of radiation in a goniometer a sulfur-lead photoresistor is used. Width of the cut on the analyzing prism is 0.127 mm; it determines the zone of linear dependence of output signal on the angle of mismatch as equal to 17".

The principle of separation of controlling signal in this goniometer is the same as in the goniometer with external source of radiation described in § 3. Controlling signals, passed to drives of the gyroscopic platform and tracking reflector, are produced by demodulators. To the demodulators, in addition to the basic signals, support signals of constant frequency and phase are fed from the photoresistor. Support signals are produced by a photodiode mounted by the modulating disk.

The examined goniometer can work simultaneously on two control prisms mounted onboard one missile. Separation of signals on two control channels is carried out with the use of the optical spectrum of the radiated signal. The goniometer works in a range of wavelengths from 0.4 to 2.8 microns. The control prism, mounted on one of the gyroscopic platforms, reflects the light rays in the range from 0.7 to 1.25 microns, and the prism erected on the other platform – in the range from 1.35 to 2.7 microns. The signals, separated with the help of optical filters found in the goniometer, move to the drives of each of the gyroscopic platforms.

§ 5. Photoelectric Synchronous Gear

A diagram of a photoelectric synchronous gear is shown in Fig. 15. It consists of transducer and receiver with a servodrive.

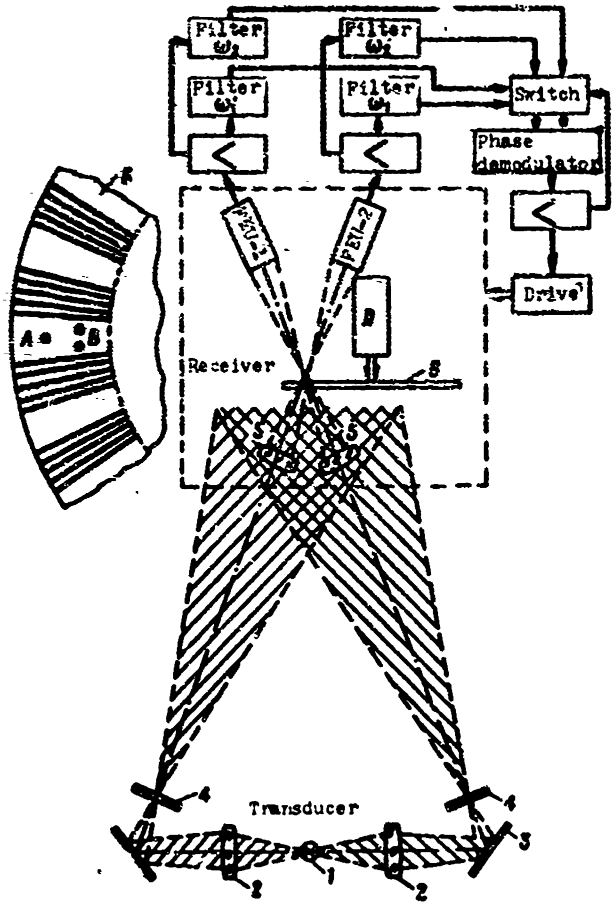


Fig. 15. Synchronous gear: 1 – tube; 2 – objective; 3 – mirror; 4 – diaphragm; 5 – objective; 6 – modulator.

Source of signal in the transducer is a tube with a vertically located filament. After passage of the condensers and reflection from end mirrors two light rays are directed upwards onto the receiver. Each of rays is limited by a diaphragm with a narrow slot.

Light rays from each of ends of transducer are focused with the help of two lenses in the plane of the modulating disk. The modulating disk, the diameter of which is 250 mm has 1000 sectors which are joined in groups of 10. During rotation of the disk packets of pulses fall on the photoelectric receivers. Occurrence rate of packets is ω_1, and frequency of pulses in a packet is ω_2 (Fig. 16).

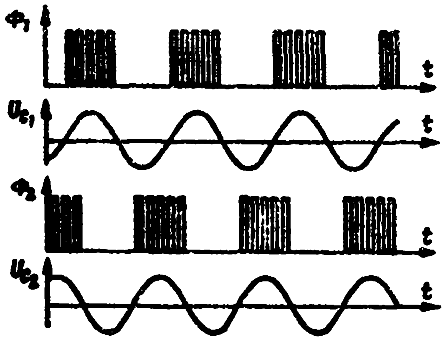


Fig. 16. Diagrams of signals.

If between the azimuthal positions of the transducer and the receiver there is no mismatch, both rays from the transducer fall in one point A (Fig. 15). Light signals, falling on the receivers of radiation, have one phase, therefore the controlling signal on the output of the demodulator equals zero.

In the case when between the positions of the transducer and receiver there is an angular mismatch, the light rays from each end of the transducer fall on different points B. Light signals, received by the receivers of radiation, will have various phases. Envelopes of frequency ω_1 on the output of the amplifiers will also be shifted in phase, therefore controlling signal on the output of the demodulator will differ from zero. This signal exerts an influence on the drive for azimuthal turning of the receiver, thus ensuring its agreement with the transducer.

The receiver of the synchronous gear can operate under two conditions: coarse – on low frequency ω_1, and fine – on high frequency ω_2. Switching of system from one condition to the other is done at an angle of mismatch equal to 30'. The switch for conditions works depending on the values of signals of frequencies ω_1 and ω_2 which are fed to it from the amplifier.

Accuracy of the synchronous gear depends on the width of the slots in the diaphragms of the transducer, distance between them, and number of sectors in the modulating disk of the receiver. For the examined synchronous gear accuracy is characterized by an error which does not exceed 0.1'.

§ 6. Photoelectric Transducers of Angles

Design and arrangement of photoelectric transducers of angles are characterized by great diversity, but all of them include the following elements: scale, source of radiation, receiver of radiation, amplifying-converting and recording devices.

In the simplest angle transducer the scale is an opaque disk with openings located around the circumference. During rotation of the scale the light rays pass through the openings onto the receiver of radiation and are converted to electrical pulses. The number of pulses fixed by a counter corresponds to the angle of rotation of the scale. A deficiency of this transducer is the impossibility of orientation of the scale on assigned readings.

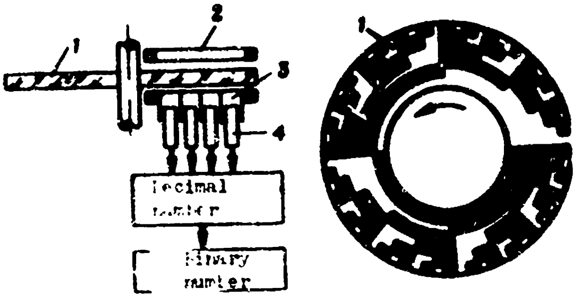


Fig. 17. Transducer of angles: 1 – scale; 2 – tube; 3 – diaphragm; 4 – receiver of radiation.

A peculiarity of a transducer with a code scale (Fig. 17) is the fact that every reading corresponds to a specific orientation of the transducer. The scale is coded in a binary numbering system. Any number in this number system constitutes a combination of only two figures: 0 and 1. Correspondence between decimal and binary numbering systems is shown in Table 3.

Table 3.

Decimal number	1	2	3	4	5	6	7	8	9	10
Binary number	0001	0010	0011	0100	0101	0110	0111	1000	1001	1010

The maximum number which it is possible to fix in a binary system at n discharges equals

$$N=2^n-1. \qquad (7)$$

A transducer with a code scale has a number of receivers of radiation corresponding to the number of discharges. Dark sections correspond to 0, and light -1. Every sector of the scale has its corresponding binary code combination.

Angles of rotation of the transducer with a code scale are fixed with the help of binary electronic counters.

The examined photoelectric transducers are single-channel. For increasing of accuracy multichannel transducers are designed. In a two-channel transducer the channel for coarse reading is constructed just as a single-channel transducer; a full turn of the scale of the channel for fine reading corresponds to a division value of the scale of the channel for coarse reading. Between the channels for coarse and fine readings there may be a kinematic or optical connection. A kinematic connection (with the help of mechanical angle reduction gears) possesses comparatively low accuracy; more exact is the optical reduction of angular values.

CHAPTER III

POLARIZATION DEVICES

§ 1. Assignment and Principle of Operation of Polarization Devices

Polarization devices are a variety of the previously examined photoelectric devices. They work on a polarized light signal. Polarization devices are used in optical synchronous gears for the transmission of oriented directions in a vertical plane and in autocollimating goniometers. As compared to the previously examined photoelectric synchronous gear, polarization synchronous gears are characterized by greater accuracy. Application of polarization devices in goniometers makes it possible, by means of splitting of a polarized light bundle, to separate the mismatch signal into two mutually perpendicular planes, i.e., to measure angles of deflection of sighting axis of goniometer from a perpendicular to the mirror surface in two directions – azimuthal and vertical.

Light rays, emitted by usual sources, are not polarized. End of a wave vector of nonpolarized light can occupy different positions in a plane which is perpendicular to the direction of its propagation. The direction of wave vector of polarized light changes in space by a specific law.

The most general case of polarization of light is elliptic polarization (Fig. 18). Components of ends of wave vector on two axes in this case will equal:

$$b_x = a_x \cdot \cos\omega t, \qquad (8)$$
$$b_y = a_y \cdot \cos(\omega t + \psi); \qquad (9)$$

where ω – frequency of rotation of vector; ψ – phase; a_x, a_y – amplitudes. In the case when $a_x = a_y = a$ and $\psi = \frac{\pi}{2}$, polarization of light is circular. If, however, $\psi = 0$, then the light signal possesses linear polarization. The wave vector of linearly polarized light lies in one plane, called the plane of polarization.

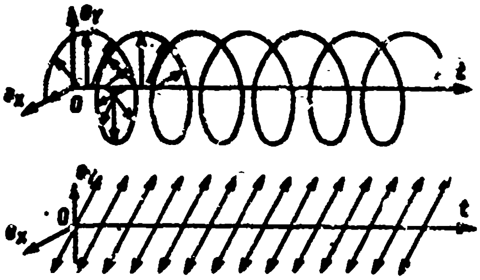


Fig. 18. Polarization of light.

Conversion of light signal in polarization devices is done with the help of polaroids, polarizing and double refracting prisms. A polaroid will convert a nonpolarizing light bundle into linearly polarized. If on the path of the polarized light a polaroid is set, the value of light flux passed will be

$$\Phi = \Phi_0 \cos^2\alpha, \qquad (10)$$

where α – angle between planes of polarization. From the given formula it follows that at $\alpha = 90°$ the value of luminous flux on the outlet of the polaroid $\Phi = 0$.

Double refracting prisms divide nonpolarized light into two bundles, polarized in mutually perpendicular planes.

For modulation of a polarized light signal polarization elements are used which change their optical properties under the impact of an electrical or magnetic field. If the electrical or magnetic field changes in time, then the nature of polarization of light rays passing through such elements also is changed with the flow of time.

§ 2. Synchronous Gear with Mechanical Modulation of Signal

A diagram of polarization synchronous gear, in which mechanical modulation of a light signal is carried out, is depicted in Fig. 19.

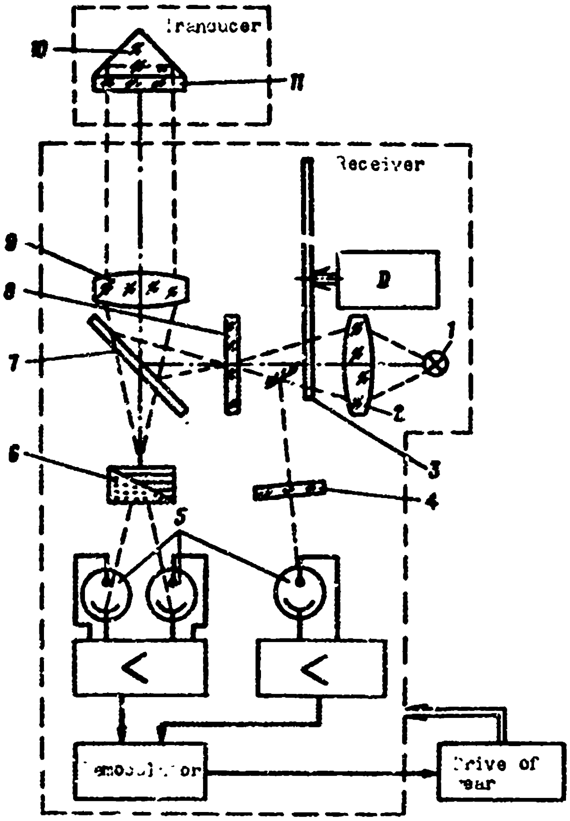


Fig. 19. Synchronous gear with mechanical modulation of signal: 1 – tube; 2 – condensor; 3 – modulator; 4 – polaroid; 5 – receiver of radiation; 6 – Wollaston prism; 7 – semitransparent mirror; 8 – double refracting crystal; 9 – objective; 10 – prism; 11 – plate.

The source of the signal (filament tube) is mounted in the receiver of the synchronous gear. After passing the condenser, the light signal is subjected to circular polarization with the help of a revolving disk made from a polaroid. At the outlet of the double refracting crystal two luminous fluxes emerge which are polarized in mutually perpendicular planes. Phases of these luminous fluxes differ by 180°.

After reflection from the semitransparent mirror the luminous flux, with the help of the objective in the form of a parallel bundle, is directed to the transducer of the synchronous gear. The transducer consists of a plate of optically active substance, possessing the property to turn the plane of polarization of incoming light and a prism. Angle of rotation of plane of polarization of light by the transducer is equal to zero in the case when it coincides with the axes of polarization of the transducer. The greater the angle between the axes of polarization of transducer and plane of polarization of light which is incident on the transducer, the greater the angle of rotation of plane of polarization of light on the output of the transducer.

The luminous flux reflected from the transducer is focused on the double refracting Wollaston prism, which is the analyzer of light signal. On the outlet of the Wollaston prism two light signals appear, each of which falls on one of the receivers of radiation. Values of these luminous fluxes equal

$$\Phi_1 = \Phi \cdot \cos^2 \alpha, \qquad (11)$$

$$\Phi_2 = \Phi \cdot \cos^2 (90^\circ - \alpha), \qquad (12)$$

and their phase differ by 180°. If the angle between the plane of polarization of light which is incident on the prism and the axes of its polarization $\alpha = 45°$, then $\Phi_1 = \Phi_2$ and on the outlet of the demodulator the mismatch signal equals zero. This corresponds to a case when the plane of polarization of light on the outlet of the objective coincides with the axes of polarization of the transducer.

In a more general case the axes of the transducer do not coincide with the plane of polarization of incident light on it, therefore the plane of polarization of output light signal will be turned on angle $\Delta\alpha$. Then the components of luminous flux on the output of the Wollaston prism will not be equal to each other:

$$\Phi_1 = \Phi \cdot \cos^2(45^\circ + \Delta\alpha), \tag{13}$$

$$\Phi_2 = \Phi \cdot \cos^2(45^\circ - \Delta\alpha). \tag{14}$$

On the output of the demodulator a constant controlling signal will appear, the polarity of which depends on the sign of angle of mismatch between axes of transducer and plane of polarization of light by the receiver, and amplitude – on the value of this angle. Controlling signal moves to the drive of the receiver of the synchronous gear, which rotates the receiver around the vertical axis up to conformity of it with the transducer.

For production of a support signal, which is fed to the demodulator, there is an auxiliary channel for conversion of the signal. Here part of the luminous flux on the output of the polaroid is fed with the help of a mirror to an additional receiver of radiation. On the path of this light signal a polaroid is set, therefore the luminous flux falling on the receiver of radiation will be modulated with the frequency of rotation of the modulator. The phase of this support light signal will be constant.

§ 3. Synchronous Gear with Electrical Modulation of Signal

In Fig. 20 is depicted the circuit of a polarization synchronous gear, in which modulation of the light signal is done with the help of a polarization device, changing its characteristics under the impact of alternating voltage applied to it.

The source of the light signal is mounted in the transducer of the polarization synchronous gear. The light signal at first passes a filter, and then with the help of a polaroid and double refracting plate is converted into a signal with circular polarization. Here the frequency of rotation of wave vector is equal to the frequency of light oscillations.

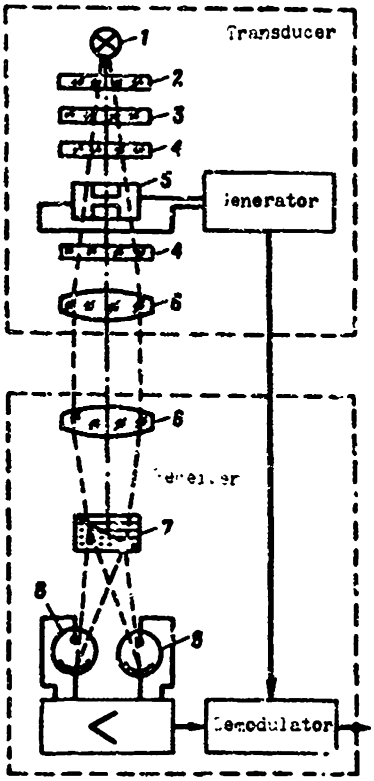


Fig. 20. Synchronous gear with electrical modulation of signal: 1 - tube; 2 - filter; 3 - polaroid; 4 - double refracting crystal; 5 - modulator; 6 - objective; 7 - Wollaston prism; 8 - receiver of radiation.

The circularly polarized luminous flux enters in a modulator, to which is applied an alternating voltage with a frequency of 200 Hz. This is produced by a generator. The modulator constitutes crystal made from potassium phosphate, KH_2PO_4, located between two electrodes. Under the impact of alternating voltage the polarizing properties of the crystal change, thanks to which the output light signal is subjected to complex polarization (Fig. 21). For one period of applied voltage the flow can be polarized circularly, on an ellipse with different orientation of semiaxes, and linearly polarized in two planes.

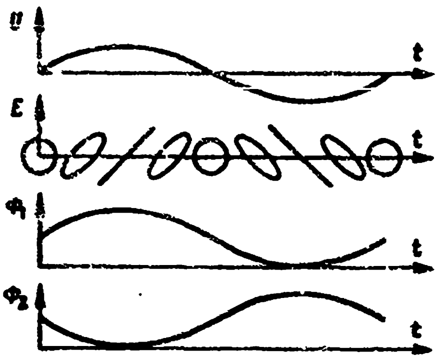


Fig. 21. Diagrams of signals.

On the output of the modulator a double refracting crystal is mounted. After the light passes it it turns out to be polarized in two mutually perpendicular planes. Components of luminous flux Φ_1 and Φ_2, which are polarized in different planes, are modulated in the antiphase. These two components of luminous flux emerge from the objective of the transducer in the form of a parallel bundle.

In receiver of the synchronous gear with the help of an objective the luminous flux is focused on an analyzer, as which a Wollaston prism is used. On its output there are two luminous fluxes, the amplitudes of which are determined by formulas (13) and (14). Each of these components falls on its own receiver of radiation.

If the axes of the prism comprise an angle $\alpha = 45°$ with planes of polarization of luminous flux by the transducer, the luminous fluxes, incident on the receivers of radiation, will be equal in amplitude and mismatch signal on the output of the demodulator will be equal to zero. In the event of a disturbance of the shown condition there will be no equality of amplitudes of luminous fluxes falling on the receivers of radiation, and the mismatch signal will be different from zero. This controlling signal can be conveyed to the drive for turning the receiver or transducer of the synchronous gear, with the help of which the receiver and transducer can be reduced to a coordinated position for azimuth.

§ 4. Polarization Goniometer

An autocollimating polarization goniometer is intended for aiming the American "Minuteman" missile during the launching of it from a mobile ground launcher. It is mounted on the missile box by its instrument section in a gimbal suspension, in which it can be rotated for aximuth and in a vertical plane. On each of the axes of the gimbal suspension a drive with a motor is mounted.

In Fig. 22 is depicted a diagram of polarization goniometer. It produces two mismatch signals. One of them is proportional to the angle of deflection of the sighting axis of the goniometer from perpendicular to the control mirror of the gyro-stabilized platform [GSP] in aximuth, and the other – in pitch. Aximuthal mismatch signal moves from the goniometer to the drive of gyroplatform, ensuring its turning for azimuth during aiming. The mismatch signal for pitch is fed to the vertical drive of the gimbal suspension of the goniometer. This drive serves for coordination of sighting axis of the goniometer with a perpendicular to the control mirror of the gyroplatform for pitch.

Main units of the goniometer are:

- radiator of light signal with modulator;

- optical system;

- two channels for separation of mismatch signals (aximuthal and for pitch).

Principle of operation of the radiator of light signal is analogous to the principle of operation of the transducer for a polarization synchronous gear with electrical modulation of light. Luminous flux from the filament tube passes an optical filter, polaroid, and double refracting plate, on the output of which it has circular polarization. On the output of the modulator there are two components of luminous flux which are polarized in a complex manner (see Fig. 21). Each of these components is shifted relative to each other by 180° in phase.

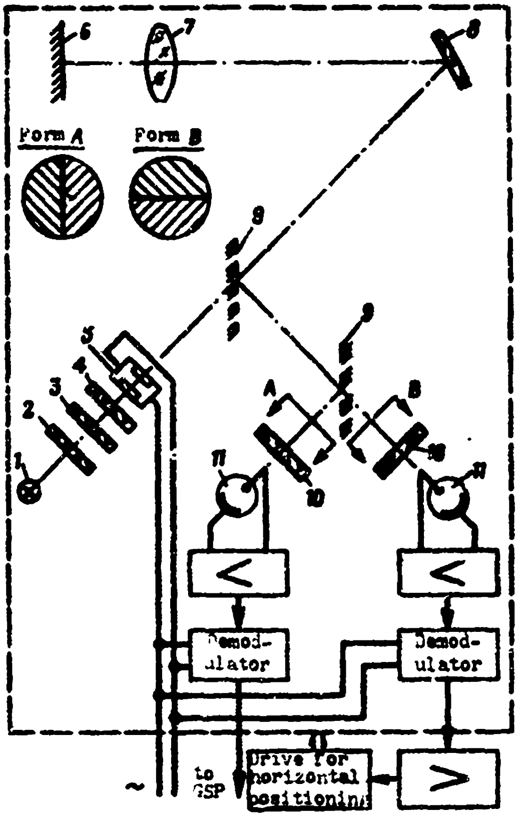


Fig. 22. Polarization goniometer: 1 – tube; 2 – filter; 3 – polaroid; 4 – double refracting crystal; 5 – modulator; 6 – control mirror; 7 – objective; 8 – mirror; 9 – semitransparent mirror; 10 – polaroid; 11 – receiver of radiation.

After passing the semitransparent mirror the light is reflected from the mirror and emerges from the objective in the form of a parallel bundle which falls on the control mirror of the gyroplatform and, being reflected from it, is focused by the objective of the goniometer on the analyzing devices.

Separation of light signal into two channels is done with the help of a semitransparent mirror. Plates made from two polaroids glued along the diameter are used as analyzers. Planes of polarization of light for each of the halves of the analyzer are perpendicular, therefore the phase of components of luminous flux passing through these halves of the analyzer differ by 180°. Analyzers are oriented in each of the channels in a different form: in the azimuthal channel the boundary of halves of the analyzer is vertical, and in the channel for pitch it is horizontal.

Principle of separation of mismatch signal in each of the channels is identical. Let us consider the principle of operation of the azimuthal channel. If the sighting axis of the goniometer is perpendicular to the control mirror in the azimuthal plane, two luminous fluxes which are equal in amplitude and opposite in phase are incident on the receiver of radiation through the analyzer. Therefore on the output of the demodulator the mismatch signal equals zero. In that case when the sighting axis of the goniometer is not perpendicular to the plane of the control mirror, luminous fluxes of different phases which are unequal in amplitude are incident through the analyzer onto the receiver of radiation. Controlling signal on the output of the demodulator will be different from zero, and its polarity corresponds to the sign of the angle between sighting axis and a perpendicular to the control mirror.

CHAPTER IV

AMPLIFYING-CONVERSION DEVICES

§ 1. Assignment and Classification

Electrical signals, taken from photoelectric receivers of radiation and other sensing devices, have a low power which is insufficient for the direct starting up of regulating and actuating devices. In certain devices of aiming systems the signals have to be amplified by 10^6 and more times.

The most widespread types of amplifiers are:

- electronic;
- semiconductor;
- magnetic.

Electronic amplifiers are characterized by high sensitivity, therefore they are capable of amplification of signals of very low power. Semiconductor elements permit the reduction in weight of amplifying devices and an increase in their reliability and service-life. However, semiconductor amplifiers possess considerable inherent noises. Magnetic amplifiers make it possible to obtain a large output power for the signal. They have a high degree of reliability in operation. A deficiency of magnetic amplifiers is their great weight.

The basic characteristic of an amplifier is amplification factor - the ratio of power or voltage on the output of the amplifier to the power or voltage on its input. For increasing the amplification factor the amplifiers are made multistaged.

If sensing device works on direct current, and the actuating device on alternating, then in the amplifying duct conversion of a constant signal into variable, which is carried out with help of modulators, should take place.

More widespread is the other case - when from the sensing device a variable signal is taken, and the actuating device works on direct current. Conversion of a variable signal into constant is done with the help of demodulators.

§ 2. Amplifiers of Photocurrents

Amplification of signals, taken from photoelectric receivers of radiation, is done by electronic and semiconductor amplifiers. Amplifiers of photocurrents, depending on the type of luminous flux which is incident on the receivers of radiation, work on direct or alternating current.

Circuit diagrams of receivers of radiation on the input of amplifiers are characterized by their great diversity. However, they can be divided into two groups: direct and balanced.

In Fig. 23 are depicted two circuits of direct amplification of photocurrents: with a photoresistor and a photomultiplier. Supply voltage is fed to the photoresistor from the anode of the amplifier tubes with the help of a voltage divider formed from two resistors R_1 and R_Φ. The amplifier is intended for amplification of variable signals. During a change of resistance of the receiver of radiation, which is induced by the light flux falling on the receiver, value of amplitude of input signal will be

$$U_1 = \frac{U_{\text{п}} \cdot R_{\text{н}} \Delta R_{\text{ф}}}{(R_{\text{н}} + R_{\text{ф}})^2}. \tag{15}$$

where $U_{\text{п}}$ - supply voltage, fed to the receiver of radiation; $R_{\text{н}}$ - load resistance. For the examined circuit diagram of the receiver the supply voltage equals

$$U_{\text{п}} = \frac{U_a R_{\text{ф}} R_{\text{н}}}{R_1 R_{\text{ф}} + R_1 R_{\text{н}} + R_{\text{ф}} R_{\text{н}}}, \tag{16}$$

where U_a - anode voltage.

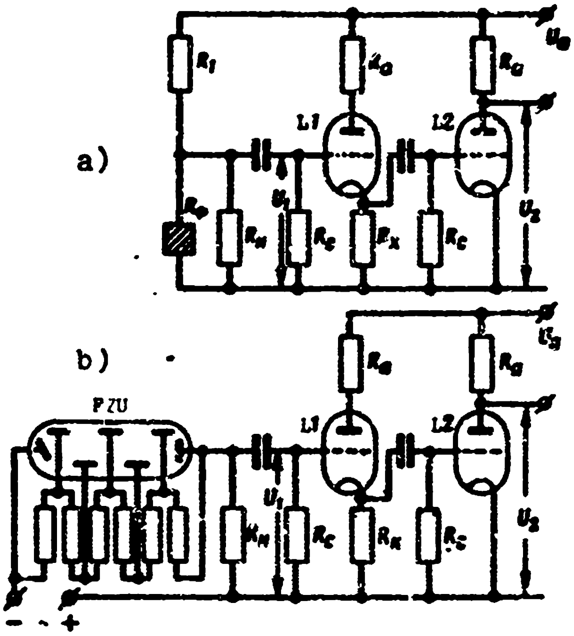


Fig. 23. Circuits of direct amplification of photocurrents: a) with photoresistor; b) with photomultiplier.

The first amplifier stage is a cathode follower. The signal is taken from the cathode load of this stage. Amplification factor of the cathode follower is approximately equal to a unit. It has a very low output resistance, therefore it is expedient to use it for coordination of receiver of radiation with the subsequent amplifier stage.

Second amplifier stage constitutes a resistor-coupled amplifier. There may be several such cascades in an amplifier of photocurrents. So that the d-c voltage does not go from the output of the previous stage to the tube grid of the subsequent cascade, their connection is realized with the help of separating capacitances.

If a photomultiplier is used as the receiver of radiation, its circuit diagram on the input of the amplifier will have a number of peculiarities. Supply voltage is fed to the photomultiplier from an autonomous source. With help of voltage divider, built on the chain of resistors R_1, R_2, R_3 ... R_n, its voltage is fed to each of the electrodes and the potentials of the electrodes increase from the cathode to the anode.

Value of input voltage equals

$$U_1 = R_{\text{н}} \Delta I, \qquad (17)$$

where ΔI – change of current in anode circuit of photomultiplier in the event of supply of a light signal on its cathode.

The first amplifier stage is a cathode follower. The second cascade constitutes a resistor-coupled amplifer.

In a balanced circuit for amplification of photocurrents (Fig. 24) on the input of the amplifier there are two receivers of radiation. The light signal is fed to only one of the receivers of radiation. Peculiarities of balanced circuit diagrams of receivers of radiation are higher sensitivity, and also stability in the event of change of temperature of receivers of radiation.

It is expedient to use a balanced circuit diagram of receivers of radiation during amplification of constant light-signals. Separating capacitances are absent between the cascades of such amplifiers.

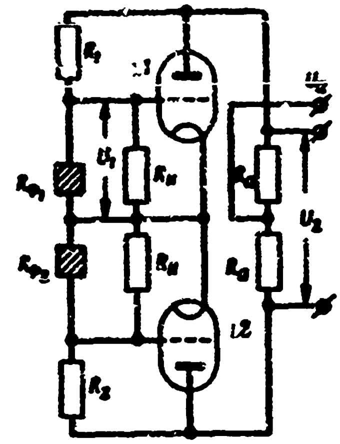


Fig. 24. Balanced circuit for amplification of photocurrents.

For amplification of photocurrents semiconductor amplifiers are also used, and in a number of cases – combined. Their first cascade is built on an electron tube, and subsequent ones – on transistors. Application of an electron tube in the first cascade permits decreasing of inherent noises of the amplifier.

§ 3. Converters of Signals

A device, converting a signal of direct current into alternating voltage, the amplitude of which is proportional to the value of input signal, but the phase corresponds to its polarity, is called a modulator. Modulators can be constructed on electron tubes and semiconductor elements.

In Fig. 25 is depicted a very widespread annular modulator on semiconductor diodes. Its operation is based on a change of resistance of semiconductor diodes depending on value of voltage applied to them.

If input voltage equals zero, then under the condition of symmetry of annular modulator the components of current in the primary winding of the output transformer which are caused by modulating voltage are compensated, since they are equal in amplitude and opposite in sign.

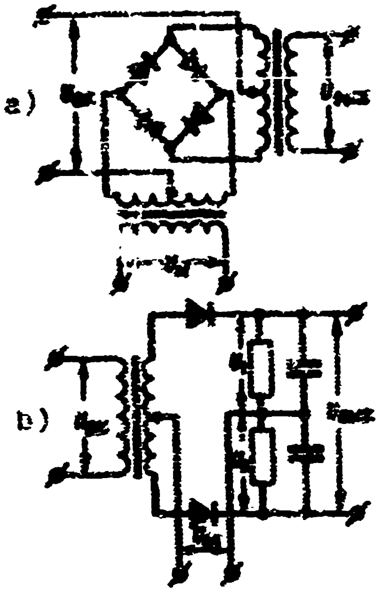


Fig. 25. Converters of signals: a) modulator; b) demodulator.

Following supply of a constant input signal on the arms of the bridge which is formed by the semiconductor diodes, the resistances of the diodes are changed. Symmetry of the annular bridge is disturbed and on the output of the modulator alternating voltage appears. If polarity of the input signal is changed, the direction of flow of the resulting current in the primary winding of the output transformer in positive and negative half-periods will be changed to the opposite. Thus, a change of polarity of input signal leads to change of phase of output signal by 180°.

Modulated light signals usually have a form which is different from sinusoidal. For conversion of such signals there are resonance amplifiers, tuned to the frequency of the basic harmonic component of the signal.

The resonance amplifier strengthens only one frequency of signal and suppresses all remaining frequencies. Therefore on the output of the amplifier the signal acquires a strictly sinusoidal form.

A phase demodulator carries out the conversions of signals reverse to those which are carried out by the modulator. It converts a signal in such a way that the constant signal obtained on the output is proportional to the amplitude of the input signal, and the polarity of the output signal corresponds to the phase of the input signal.

The simplest arrangement for a phase demodulator is a half-wave circuit containing diodes. On the demodulator the signal which is subject to conversion is fed, and a support signal with a constant phase and amplitude.

If input voltage coincides in phase with support, then components of the output signal in the upper and lower halves of the demodulator will be

$$U_1 = c\,(U_{\text{оп}} + U_{\text{вх}}),$$
$$U_2 = c\,(U_{\text{оп}} - U_{\text{вх}}).$$

Total output signal equals

$$U_{\text{вых}} = 2cU_{\text{вх}}. \qquad (18)$$

In the case when input voltage is opposite to support in phase, we have

$$U_1 = c\,(U_{\text{оп}} - U_{\text{вх}}),$$
$$U_2 = c\,(U_{\text{оп}} + U_{\text{вх}}).$$

Output signal in this case will equal

$$U_{\text{вых}} = -2cU_{\text{вх}}. \qquad (19)$$

A filter mounted on the output of the demodulator serves for smoothing out the pulsations of the input signal.

CHAPTER V

INDUCTION SYNCHRONOUS GEARS

§ 1. Application of Synchronous Gears In Aiming Systems

Induction synchronous gears serve for solution of the following problems:

- telemetry of angles of turning of different elements;

- remote turning of various elements on specific angles;

- synchronous rotation of several axes which are not connected with each other mechanically.

They are used for direct remote-control turning of the missile, the gyroscopic platform, or the goniometer on definite angles. Besides this the synchronous gears are used for remote-control transmission of angular values, measured by a goniometer working under measuring conditions.

Induction synchronous gears have fundamental distinction from the photoelectric and polarization synchronous gears examined earlier: they do not possess the property of rigidity. The property of rigidity of photoelectric and polarization synchronous gears amounts to the fact that during their operation a clear spatial correspondence between orientation of transducer and receiver is ensured. The transducer and receiver of an induction synchronous gear in a coordinated position can have an arbitrary spatial orientation. This peculiarity of induction synchronous gears does not permit using them for vertical transmission of oriented directions.

The second distinction of induction synchronous gears from polarization gears is their lower accuracy.

§ 2. Elements of Synchronous Gears

Induction synchronous gears can be classified by different criteria. Depending on operating conditions they are divided into indicator and transformer. An indicator synchronous gear includes a transducer and a receiver which is connected with it electrically. If the transducer is turned on a certain angle, in the receiver as a result of the interaction of magnetic fluxes there is a synchronizing moment, turning the receiver on the same angle. A transformer synchronous has, in addition to the transducer and receiver, an amplifying-conversion device and drive for turning the receiver. In the event of turning of the transducer a mismatch signal is taken from the receiver of the synchronous gear. After amplification it is fed to a drive, thus turning the receiver until it corresponds with the transducer.

Depending on the number of channels in a synchronous gear they are divided into single- and multichannel. Multichannel synchronous gears posses greater accuracy. Communication between channels of a synchronous gear can be mechanical or electrical. In the first case in a synchronous gear they use mechanical, and in the second – electrical reduction of angular values.

The most widespread types of transducers and receivers of synchronous gears are the selsyn and rotary transformers.

In Fig. 26 are depicted two synchronous gears which are constructed on these elements.

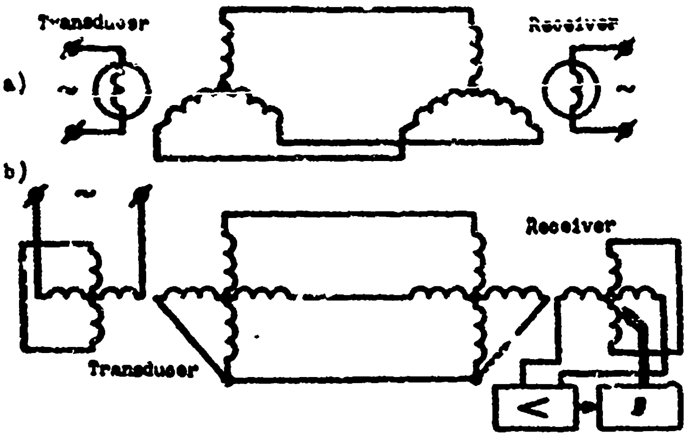


Fig. 26. Synchronous gears: a) on selsyns; b) on rotary transformers.

Selsyns are machines of alternating current. They have a single-phase excitation winding and a three-phase secondary circuit made from three windings, the axes of which are shifted relative to one another by 120° in circumference. All three windings are united by a star. The excitation winding can be disposed both on the stator and also on the rotor.

Two selsyns with united ends of secondary windings form a synchronous gear. One of the selsyns in this case is the transducer, and the second the receiver.

If between the stator and rotor of the transducer there is angle of mismatch $\alpha_{д}$, and between stator and rotor of receiver $\alpha_{п}$, then as a result of the interaction of magnetic fields of windings the following moment will act on the rotor of the receiver

$$M'_{п} = M_{max} \cdot \sin(\alpha_{д} - \alpha_{п}). \tag{20}$$

The rotor of the transducer in its turn will be influenced by moment

$$M_{д} = M_{max} \cdot \sin(\alpha_{п} - \alpha_{д}). \tag{21}$$

Both these moments strive to equalize angles $\alpha_{п}$ and $\alpha_{д}$. For this reason the moment of rotation of selsyn rotors is called synchronizing.

On the shaft of the selsyn-receiver moment of friction $M_{\text{тр}}$ can act then

$$M_{\text{тр}} = M_{\text{мах}} \cdot \sin\Delta\alpha$$

or

$$\Delta\alpha = \arcsin\frac{M_{\text{тр}}}{M_{\text{мах}}}\,. \tag{22}$$

Angle $\Delta\alpha$ is the error of the selsyn gear.

Accuracy of a synchronous gear is its basic characteristic. In addition to the moment of friction, the accuracy of a synchronous gear is influenced by industrial errors. Depending on errors of manufacture selsyns are divided into the four classes which are given in Table 4.

Table 4.

Class of accuracy	1	2	3	4
Permissible error	$0^\circ.75$	$1^\circ.5$	$2^\circ.5$	5°

Based on their constructions, selsyns are contact and contactless. In contact selsyns there are contact rings and brushes, increasing the moment of friction and lowering the reliability of performance. Directly on the stator of a contactless selsyn there are two windings: excitation and three-phase secondary. The rotor of such a selsyn does not have windings, it consists of two halves of a special form which are assembled from iron plates. The rotor ensures a magnetic connection between the primary and secondary windings. During its rotation an electromotive force, depending on angle of rotation is induced in the secondary circuit.

Rotary transformers have on the rotor two mutually perpendicular single-phase windings, one of which is an excitation winding, and the second is a short-circuit. On the stator there are also two secondary windings: sine and cosine. During turning of the rotor of the rotary transformer relative to the stator in the secondary windings electromotive forces are induced which are equal to

$$U_1 = U_{max} \sin \alpha, \quad (23)$$

$$U_2 = U_{max} \cos \alpha. \quad (24)$$

Synchronous gears on rotary transformers work only in a transformer regimen. During rotation of the rotor of the transducer the electromotive force is induced not only in the windings of its stator, but also in the windings of the stator of the receiver which are joined with them. Due to this in the winding of the rotor of the rotor of the receiver a voltage develops, the phase of which depends on the sign of the angular mismatch between the rotors of the receiver and the transducer. This voltage is fed to the amplifier and control winding of the motor. The motor leads the rotor of the receiver into a position which coincides with the rotor of the transducer.

The main causes of errors for rotary transformers are a nonperpendicular condition of stator windings and inequality of coefficients of mutual induction of sine and cosine windings. Errors of rotating transformers of different classes are given in Table 5.

Table 5.

Class of accuracy	0	1	2	3
Error from nonperpendicular condition of windings.	2'	3'5	6'	8'
Error from inequality of coefficients of mutual induction	3'	5'	8'	12'

It follows from the table that accuracy of manufacture of rotary transformers is considerably higher than the accuracy of manufacture of selsyns. Therefore synchronous gears on rotary transformers possess a higher degree of accuracy.

§ 3. Multichannel Synchronous Gears With Mechanical Reduction

For an increase of accuracy multichannel synchronous gears are used. Rotors of transducers of neighboring channels and rotors of the receivers are connected with help of mechanical reduction gears. In Fig. 27 is depicted the circuit of a two-channel synchronous gear in which the rotors of the transducers for fine and coarse readings are connected by a reduction gear with a gear ratio of n:1, and the rotors of the receivers – by a reduction gear with a gear ratio of 1:n.

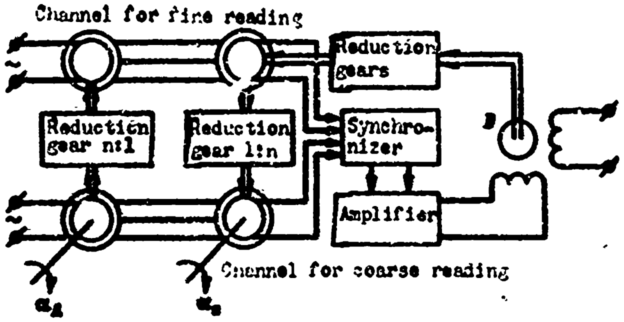


Fig. 27. Two-channel synchronous gear.

In the event of angular mismatch between the positions of rotors of the transducers and receivers, on the output of the receivers mismatch signals appear, which after amplification are fed to the controlling motor. The controlling motor turns the rotor of the receiver of the channel for fine reading until there is coincidence of the rotors of the receivers with the rotors of the transducers. Voltages of mismatch from rotors of the receivers are fed to the motor in turn: at large angles of mismatch the motor is controlled from the receiver of the channel for coarse reading, and at small angles – from the receiver of the channel for fine reading. Switching of channels is done with the help of a sychronizing device.

Let us consider the influence of mechanical reduction between channels on the accuracy of a synchronous gear.

In the presence of error of transmission of angular values the output voltages of channels for coarse and fine readings will be equal respectively

$$U_{\text{г}} = U_{\max} \cdot \sin(\alpha_{\text{п}} - \alpha_{\text{д}}) + \Delta U,$$
$$U_{\text{т}} = U_{\max} \cdot \sin n(\alpha_{\text{п}} - \alpha_{\text{д}}) + \Delta U,$$

where ΔU - voltages of errcrs.
Angular errors have the form:

$$\Delta\alpha_{\text{г}} = \frac{\Delta U}{k}, \tag{25}$$

$$\Delta\alpha_{\text{т}} = \frac{\Delta U}{nk}, \tag{26}$$

where k - sensitivity of channel for coarse reading.

Thus the error of a two-channel synchronous gear decreases by n times.

In order to obtain the full error of a synchronous gear it is necessary to add in formula (26) the error of the reduction gear, then

$$\Delta\alpha_{\text{т}} = \frac{\Delta\alpha_{\text{г}}}{n} + \Delta\alpha_{\text{р}}. \tag{27}$$

Consequently the accuracy of a synchronous gear is influenced significantly by error in the manufacture of the reduction gear.

Let us consider now the accuracy of a three-channel synchronous gear, having channels for coarse, average, and fine readings. Error of the channel for average reading equals

$$\Delta\alpha_{\text{с}} = \frac{\Delta\alpha_{\text{г}}}{n} + \Delta\alpha_{\text{р}},$$

and error of the channel for fine reading will be

$$\Delta\alpha_{\text{т}} = \frac{\Delta\alpha_{\text{с}}}{n} + \Delta\alpha_{\text{р}}.$$

Placing in the last formula the value $\Delta\alpha_c$, we have

$$\Delta\alpha_{\text{т}} = \frac{\Delta\alpha_{\text{г}}}{n^2} + \frac{\Delta\alpha_{\text{р}}}{n} + \Delta\alpha_{\text{р}}. \tag{28}$$

From the dependence obtained it is clear that the limit of accuracy of multichannel synchronous gears is determined by errors in the reduction gear. The influence of errors in the manufacture of transducers and receivers of the synchronous gear in multichannel gears is essentially reduced, therefore in them there is the possibility of using selsyns and rotary transformers of low classes of accuracy.

Application of a reduction gear in a synchronous gear leads to a disturbance of self-synchronization of the channel for fine reading at angles of mismatch

$$\Delta\alpha > \frac{360^\circ}{2n}.$$

This is caused by the presence of n stable positions of the channel for fine reading within the limits of 360°, at which the voltage of mismatch on the output of the receiver equals zero. The channel for coarse reading serves to ensure the self-synchronization of a synchronous gear at large angles of mismatch.

In Fig. 28 graphs of change are shown for voltages of mismatch on the output of receivers of channels for coarse and fine readings. Angle of switching of the synchronous gear $\Delta\alpha_n$ from the coarse to the fine channel should be less than half the half-period of change for the signal of the channel for fine reading, but on the other hand it should not be less than double the error in the channel for coarse reading

$$2\Delta\alpha_r < \Delta\alpha_n < \frac{360^\circ}{2n} - 2\Delta\alpha_r. \qquad (29)$$

Thus for n = 30 and a selsyn gear of the first class of accuracy the angle of switching should be found within the limits $1.5^\circ < \Delta\alpha_n < 4^\circ.5$.

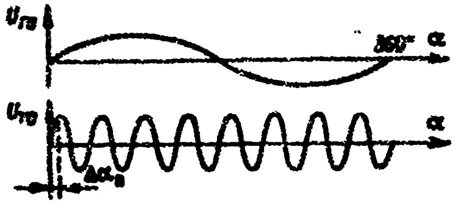


Fig. 28. Diagrams of voltages.

From inequality (29) it follows that in the selection of gear ratio n and class of accuracy of a synchronous gear it is necessary to observe the condition

$$\frac{360^\circ}{2n} > 4\Delta a_r \tag{30}$$

or

$$n < \frac{45^\circ}{\Delta a_r}.$$

In the case of nonobservance of this condition it is impossible to ensure the steady operation of a synchronous gear during switching of channels.

§ 4. Synchronizers

The most widespread types of synchronizers are synchronizers on electron tubes and semiconductor diodes. Diagrams of them are shown in Fig. 29. A synchronizer on electron tubes has two inputs; voltage from the channel for fine reading through resistors R_1 and R_2 is applied directly to the input of the amplifier, and voltage from the channel for coarse reading is supplied preliminarily on the amplifying cascade. In the anode circuit of this amplifying cascade stands a transformer; its neon tubes are connected to the input of the amplifier in parallel with voltage of the channel for fine reading.

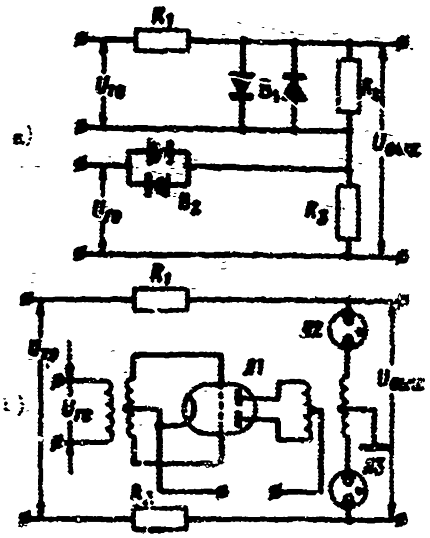


Fig. 29. Synchronizers: a) on diodes; b) with neon tubes.

If the angle of mismatch between the rotors of the receiver and transducer $\Delta\alpha < \Delta\alpha_n$, the voltage of the channel for coarse reading is small and on the output of the amplifying cascade the voltage will be insufficient for ignition of the neon tubes. In this case voltage from the fine channel is fed to the input of the amplifier, and voltage from the channel for coarse reading is suppressed, since the output of the amplifying cascade is disrupted by nonburing neon tubes.

In the case when angle of mismatch $\Delta\alpha > \Delta\alpha_n$, the output voltage of the amplifying cascade becomes larger than the potential of ignition of neon tubes. Here the voltage of the fine channel is short-circuited through the burning tubes, and voltage from the channel for coarse reading is switched to the input of the amplifier.

The action of a synchronizing device on semiconductor diodes is based on the property of semiconductor diodes to change their resistance depending on the voltage applied to them. At small values of applied voltage the resistance of the diode is great, and upon achievement of a specific level of voltage it drops sharply.

In the channel for fine reading the resistance R_2 is considerably larger than resistance R_1. With a small voltage of mismatch the resistances of rectifiers B_1 and B_2 are very great.

At small angular mismatches on resistance R_2 arrives voltage from the channel for fine reading which is applied to the input of the amplifier. Output voltage from the channel for coarse reading falls on rectifier B_2.

If angular mismatch increases, then due to increasing voltages appearing on the outputs of channels for coarse and fine readings there is a sharp decrease of resistances of rectifiers B_1 and B_2. Rectifier B_1 will shunt resistance R_2, and a large part of the voltage of mismatch for the fine channel falls on resistance R_1. Due to the low resistance of rectifier B_2, voltage from the coarse channel will fall on resistance R_3, therefore it will be completely applied to the input of the amplifier.

In order to ensure steady work of the synchronizer during switching of the amplifier from one channel to another a thorough selection of resistances R_1, R_2, and R_3 is carried out, and also of characteristics of diodes of rectifiers. With these characteristics the switching of channels should be performed at an angle of mismatch which is determined by inequality (29).

§ 5. Multichannel Synchronous Gears With Electrical Reduction

In synchronous gears with electrical reduction multipolar transducers and receivers are used. Therefore with a full turn of the transducer a multiple change of voltage on its output occurs. The number of periods of change of voltage on the output of the transducer for one of its turns is equal to the gear ratio of electrical reduction.

If as the transducer of the synchronous gear a multipolar rotary transformer is used, and as the receiver – bipolar, the accuracy of reading angles with the help of the receiver is increased. On the output of the receiver the signal equals

$$U_{n} = U_{max} \sin(\alpha_{n} - \alpha_{x}),$$

and on the output of the transducer it will equal

$$U_{x} = U_{max} \sin n(\alpha_{n} - \alpha_{x}),$$

where n – gear ratio, equal to the number of pairs of poles of the transducer. Therefore the error of measurement of angle with help of a synchronous gear equals

$$\Delta\alpha = \frac{\Delta\alpha_n}{n}, \qquad (31)$$

where $\Delta\alpha_n$ – error of receiver.

A single-channel synchronous gear with multipolar transducers does not possess the property of self-synchronization, since the number of false agreements of transducer with receiver for one turn of the transducer is equal to the gear ratio of electrical reduction. For elimination of this deficiency two-channel synchronous gears have been developed. Transducers for fine and coarse readings are rigidly secured on one axis, therefore errors of mechanical reduction gears are excluded here. In the absence of mechanical reduction gears there is a decrease of moments of friction in the axes of transducers and receivers, which is also the reason for an increase of accuracy of synchronous gears with electrical reduction.

With an increase in the number of pairs of poles for the transducer the form of curve of output voltage with a change of angle of rotation of the transducer differs from a sinusoid, which has an influence on the lowering of accuracy of multipolar transducers. For increasing the accuracy of manufacture of such transducers it is necessary to increase their dimensions. Value of error of a rotating transformer with 24 pairs of poles does not exceed 1'.

A higher degree of accuracy is possessed by multipolar transducer-inductosyns. The stator and rotor of the inductosine are prepared on glass disks. On rotor there is a single-phase winding, and on the stator – a two-phase, similar to the sine-cosine winding of a rotary transformer. With the number of pairs of poles equal to 108, and diameter of transducer equal to 80 mm, the error of the inductosine does not exceed 5".

An inductosyn synchronous gear does not possess self-synchronization, therefore it is made multichannel. In its channel for coarse reading rotary transformers are used.

CHAPTER VI

GYROSCOPIC DEVICES

§ 1. Problems Solved by Gyroscopic Devices During Aiming

Gyroscopic devices obtained wide propagation in missile technology. Application of gyroscopic measuring devices in inertial control systems ensures movement of a missile on a programmed trajectory.

The operation of aiming systems is intimately connected with onboard gyroscopic instruments, since the mission of azimuthal aiming is orientation of axes of sensitivity of these instruments relative to the plane of launching (see Chapter I).

However, gyroscopic devices are also used directly during the aiming of missiles. There are three basic areas of use of gyroscopic devices in aiming systems:

- preservation of oriented geodetic directions;

- autonomous determination of azimuths of oriented directions;

- stabilization in space of elements of aiming systems when they are influenced by various mechanical disturbances.

Gyroscopic devices, serving for preservation of oriented geodetic directions, frequently are not included in the composition of aiming systems. Thus, they find application in navigational systems used for plotting the course of submarines – carriers of ballistic missiles. Direction, fixed by a directional gyroscope or gyroazimuth of a navigational system, is transferred with the help of synchronous gears to the system for aiming of missiles when they are launched from a submarine. Analogous gyroazimuths can be used also on ground mobile launchers.

Autonomous determination of azimuths of oriented directions is done with the help of gyroscopic compasses. The gyroscopic compass can be constructively united with the gyroazimuth. In the case of shifting the launcher it works under conditions of a gyroazimuth, and on a halt prior to launching the missile – under conditions of a gyrocompass.

The onboard gyroscopic instruments can also work under conditions of a gyrocompass. Aiming with the use of onboard gyroscopic instruments does not require the presence of oriented geodetic directions, since the direction of the meridian is determined directly by the onboard instruments.

For stabilization of elements of the aiming systems when there are mechanical disturbances (wind rolling of rocket, vibration of launcher during operation of different motors, etc.) it is possible to use gyroscopic stabilizers, on which these elements are mounted. In certain cases on a stabilized platform with the elements of the aiming system which are mounted on it there are no gyroscopes. As transducers of attitude for such a platform onboard gyroscopic instruments are used. Transmission of information from onboard gyroscopic instruments to the platform is carried out with the help of synchronous gears or by autocollimating means.

§ 2. Basic Properties of Gyroscopes

Gyroscope is the name given to a body which is spinning rapidly with respect to the axis of symmetry and which is mounted in a gimbal suspension.

The most widespread are gyroscopes, in which the rotating body is the rotor of an a-c motor. The stator of this motor is secured in a housing which serves as the inner frame of the gimbal suspension. Less widespread are gyroscopes, the rotor of which is rotated with the help of compressed gas. On one axis a turbine is secured with the rotor of such a gyroscope.

A balanced gyroscope is a gyroscope, the center of gravity of which coincides with a fixed point of the suspension – point of intersection of axes of the gimbal suspension. A balanced gyroscope, in which frictional forces in the axes of the suspension and frictional forces of the rotor against the air are negligible, is called free.

For decreasing friction on the axes of a gimbal suspension of a gyrsocope high-quality bearings are used: ball, with gas, electromagnetic, and electrostatic suspension, etc. For the purpose of decreasing friction against air a high vacuum is created in the gyroscope. The gyroscope box of certain instruments are filled with helium, the density of which is considerably less than air density at the same pressure.

Center of gravity of certain gyroscopes are shifted by a certain value with respect to a point of the suspension. Such gyroscopes are called heavy.

A gyroscope can have three degrees of freedom: rotation around its own axis, around the horizontal axis, and around the vertical axis of the gimbal suspension (see Figs. 3 and 4). If the outer frame of the gimbal suspension is secured the gyroscope becomes two-stage.

A gyroscope possesses two basic properties:

- stability, including the tendency to preserve a fixed position of axis of rotation in space;

- the property of precession.

A free gyroscope can arbitrarily preserve its position relative to a system of coordinates which is fixed in space for a long time. In case of the influence of short-term disturbances of the shock type on a gyroscope the position of its axis of rotation practically remains constant. Here it acquires small high-frequency oscillations which are called nutational.

Nutational oscillations of the axis of a gyroscope will be less, the greater its angular momentum

$$H = J \cdot \Omega \tag{32}$$

where Ω - angular velocity of ration of rotor; J - moment of inertia of rotor. Moment of inertia of a rotor of cylindrical form equals

$$J = \frac{mr^2}{2},$$

where m - mass; r - radius of cylinder.

Angular momentum can be increased at the expense of an increase in the mass of the gyroscope m, radius r, or rate of rotation of the rotor Ω. Rates of rotation of gyroscope rotors can reach 60,000 r/min

The property of precession of a gyroscope amounts to the fact that in the case of application of torque on one of the axes of the frames of the gimbal suspension rotation of the gyroscope develops around the other axis of the suspension. Thus if force $\bar{P}$ or torque $\bar{M}$ is applied to the inner frame of the gyroscope then precession movement of the gyroscope develops around the axis of the outer frame.

The value of angular velocity of precession equals

$$\omega_{\text{пр}} = \frac{M}{H}. \tag{33}$$

Direction of precession can be determined by following this rule: during the action of moment of external forces on a gyroscope the vector of angular momentum $\bar{H}$ strives to combine with the vector of moment of external forces $\bar{M}$ by the shortest path.

The examined two properties are possessed only by a three-stage gyroscope. In the event of restriction of one of its degree of freedom the gyroscope also loses the property of stability and property of precession.

§ 3. Gyroazimuths

A free gyroscope can be used as a gyroazimuth (Fig. 30). In the preservation of oriented direction by a gyroazimuth the previously examined property of stability of a gyroscope is used. However, a free gyrosocope strives to preserve the initial direction of axis of the rotor relative to a fixed system of coordinates. A free gyroscope cannot hold an oriented direction with respect to a system of coordinates which is connected with the earth, since due to rotation of the earth the axis of the gyroscope will be continuously deflected on azimuth and from the plane of the horizon.

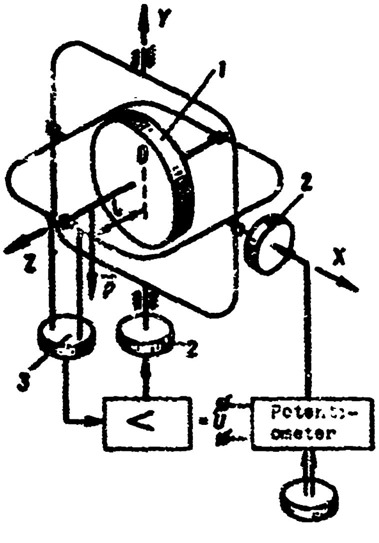


Fig. 30. Gyroazimuth: 1 – rotor; 2 – moment transducer; 3 – transducer of vertical.

Components of angular velocity of rotation of the earth on two directions (Fig. 31) equal:

$$\omega_x = \Omega_3 \cdot \cos\varphi, \quad (34)$$
$$\omega_y = \Omega_3 \cdot \sin\varphi, \quad (35)$$

where Ω_3 – angular velocity of rotation of earth; ϕ – latitude of standing point. Rate of azimuthal drift of axis of gyroazimuth depending on latitude is given in Table 6. For maintaining the axis of the rotor of the gyroazimuth in the assigned direction relative to the plane of horizon and for azimuth it is necessary to introduce a correction.

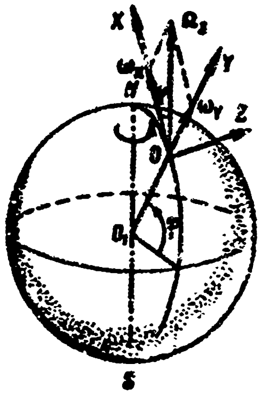


Fig. 31. Components of angular velocity of rotation of the earth.

Table 6.

Latitude, deg	43	44	55	60
Rate of drift, deg/h	10,3	10,5	12,3	13,5

To ensure correction of the gyroscope relative to the plane of the horizon it is necessary to apply torque to its vertical axis equal to

$$M_y = H\Omega_3 \cdot \cos\varphi.$$

This torque will elicit precession of the gyroscope around axis OX with angular velocity

$$\omega_x = \Omega_з \cdot \cos\varphi_т$$

ensuring that the axis of the gyroscope follows the plane of the horizon.

Position of the plane of the horizon can be determined with the help of a vertical transducer secured on the inner frame of the gyroscope (Fig. 30). Mismatch signal, taken from the vertical transducer, after amplification is fed to the torque transducer, which is secured on the vertical axis of the gyroazimuth and which applies torque to the vertical axis, thus causing precession of the gyroscope up to elimination of mismatch between the axis of the gyroscope and plane of the horizon.

For correction of vertical component of angular velocity of the earth sometimes the method of displacement of center of gravity of the gyroscope along its axis of rotation is used. For this on the gyroscope housing is affixed load P, which creates relative to the horizontal axis a torque, causing precession of the gyroscope around the vertical axis with an angular velocity equal to ω_y, but opposite to it in sign. The arm of location of load relative to the center of the gimbal suspension is determined by the formula

$$l = \frac{H\Omega_з}{P} \sin\varphi.$$

With a change of latitude of the standing point of the gyroaziumth the arm of load should be changed.

Correction of vertical component of angular velocity of the earth can be carried out with the help of a torque transducer mounted on the horizontal axis of gyroscope. From the potentiometric pickup d-c voltage is fed to the torque transducer. The amount of voltage is selected depending on the latitude of the standing point of the gyrocompass.

§ 4. Gyrocompasses

With the help of gyroscopic compasses determination of oriented geodetic directions is carried out. The axis of the rotor of the gyrocompass, due to the action of directional moment during rotation of the earth, possesses a selectivity with respect to the direction of the meridian.

Gyroscopic compasses are of two types: rated and free.

Arrangement of a rated gyrocompass is depicted in Fig. 32. It constitutes a free gyroscope, in which the inner frame of the gimbal suspension is fastened to the outer.

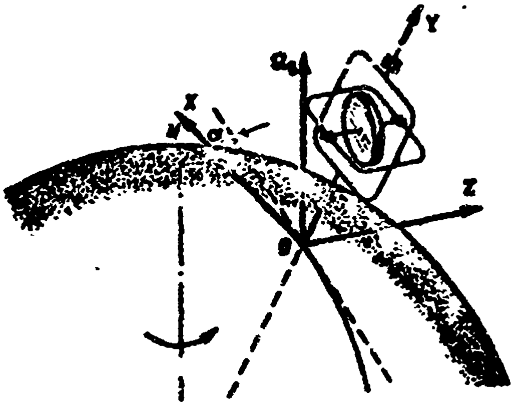


Fig. 32. Sketch of a rated gyrocompass.

Principle of operation of a gyrocompass amounts to the following. Let us assume that in the initial position the axis of the gyrorotor is found in a horizontal plane and is deflected from the plane of the meridian by an angle of 90° − α. Then due to rotation of the plane of the horizon the gyroscope will rotate around a horizontal axis with angular velocity

$$\omega_y = \Omega_3 \cdot \cos\varphi \cdot \sin(90^\circ - \alpha), \qquad (36)$$

The directional moment developing here

$$M_{\text{н}} = H\Omega_{\text{з}} \cdot \cos\varphi \cdot \sin(90^\circ - \alpha)$$

causes precession of the gyroscope around a vertical axis in a direction to the plane of the meridian.

If the friction moment in the supports of the vertical axis equals zero, then the axis of the gyroscope will accomplish sustained oscillations relative to the plane of the meridian. The period of these oscillations will equal

$$T = 2\pi \sqrt{\frac{B}{H\Omega_{\text{з}} \cos\varphi}}, \tag{37}$$

where B – equatorial moment of inertia of gyrosocpe in the gimbal suspension. For latitude $\phi = 60^\circ$ the period of oscillations of axis of a gyrocompass usually does not exceed one minute.

As a result of the action of friction moment oscillations of the axis of the gyroscope fade and it is set with a certain error in the direction of meridian. Error of the gyrocompass is determined by the inequality

$$M_{\text{тр}} < M_{\text{н}} = H\Omega_{\text{з}} \cdot \cos\varphi \cdot \sin\Delta\alpha,$$

Hence the error of gyrocompass

$$\Delta\alpha = \arcsin \frac{M_{\text{тр}}}{H\Omega_{\text{з}} \cos\varphi}. \tag{38}$$

For increasing the accuracy of the gyrocompass it is necessary to decrease the moment of friction. For this purpose liquid and gas supports are used in gyrocompasses.

The most prevalent are free gyrocompasses. A free gyrocompass constitutes a heavy gyroscope, in which the directing moment appears at the expense of displacement of the center of gravity downwards relative to the suspension point.

Principle of operation of a free gyrocompass is shown in Fig. 33. Under the effect of gravity the gyroscope housing always strives to take a vertical position. In the case of a horizontal position for the axis of the gyrorotor the force of gravity of the pendulum passes exactly through the center of the suspension and does not create torque relative to it. In process of rotation of the earth the gyroscope preserves the position of its axis, which here is deflected from the plane of the horizon.

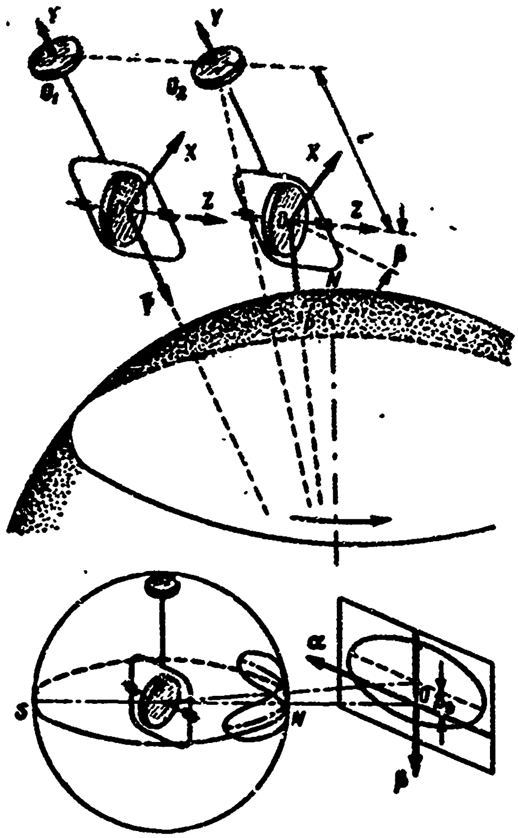


Fig. 33. Principle of operation of a free gyrocompass.

Deviation of the line, connecting the suspension point with the center of gravity, from vertical leads to appearance of pendular directing moment relative to axis OX

$$M_x = Pl\sin\beta, \qquad (39)$$

where P – weight of gyroscope housing; l – distance between suspension point and center of gravity; β – angle of deflection of axis of gyroscope from horizon. Directing moment causes the appearance of precession motion of the gyroscope relative to the vertical axis; here the axis of the gyroscope is precessed in the direction of the meridian. When the axis of the gyroscope approaches the meridian the rate of precession increases, since the angle of deviation of the axis from the plane of the horizon and, consequently, also the directing moment increase. After the axis passes the plane of the meridian the angle decreases, since the axis of the gyroscope rises. When the axis of the gyroscope reaches an extreme point the pendular moment changes its sign and the gyroscope starts to precess in the opposite direction.

The trajectory, described by the axis of the gyroscope during its precession, in a section with a certain plane constitutes a vertically flattened ellipse. Period of oscillation of the axis of the gyroscope during its precessional motion equals

$$T=2\pi\sqrt{\frac{H}{Pl\Omega_0\cos\varphi}}. \qquad (40)$$

Center of the ellipse deviates from the plane of the horizon by angle

$$\beta_0=\frac{H}{Pl}\Omega_0\sin\varphi.$$

Comparative calculations of periods of oscillations of rated and free gyrocompasses by the formulas (37) and (40) accordingly show that the period of oscillations of a free gyrocompass can be ten times greater than the period of oscillations of a rated gyrocompass. Thanks to this the free gyrocompass is stabler to outside disturbances.

For determination of direction of the meridiam the gyrocompass is equipped with a theodolite and special reading device. With the help of the reading device determinations are made of readings O_1, O_2, O_3, and O_4, corresponding to the four points of reversion of axis of the gyrosocpe durings its oscillations relative to the meridian. A reading, corresponding to the direction of the meridian, is determined by formula

$$O=\frac{1}{2}(O'+O''), \tag{41}$$

where

$$O'=\frac{1}{2}\left(\frac{O_1+O_3}{2}+O_2\right),$$
$$O''=\frac{1}{2}\left(\frac{O_2+O_4}{2}+O_3\right).$$

In the presence of three points of reversion for a determination of the direction of the meridian the following formula is used

$$O=\frac{1}{4}(O_1+2O_2+O_3)-\frac{(O_1-O_3)^2}{8(O_1-O_2)}. \tag{42}$$

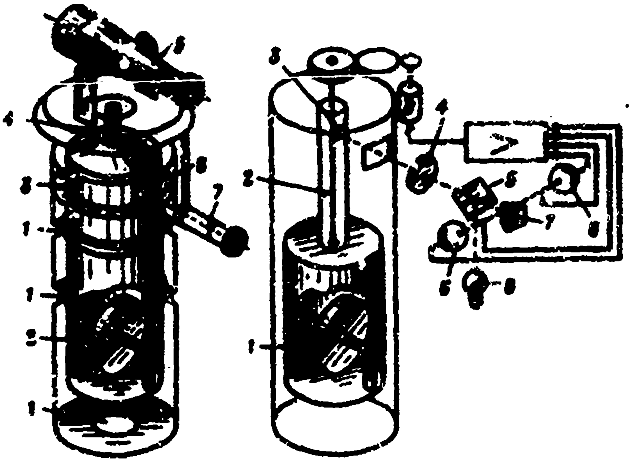
These formulas make it possible to allow for damping of oscillations of the gyroscope, appearing as a result of the presence of friction moment in its suspension.

Free gyrocompasses exist in two constructive varieties: with suspensions on a spire and on a torsion bar.

In a gyrocompass with the suspension on a spire (Fig. 34) the gyroscope housing constitutes a float placed in a reservoir with liquid. The gyroscope housing has little positive buoyancy. It is centered with the help of a steel spire, to which a step bearing is tightened. For purpose of decreasing friction agate step bearings are used.

For filling the reservoir usually a mixture of alcohol with water is used. Dissolved in it is small amount of borax, which ensures the electrical conductivity of the liquid. Supply voltage is fed to the gyromotor through supporting liquid; for this purpose on the gyroscope housing and reservoir there are three annular electrodes.

Determination of readings corresponding to points of reversion is done by autocollimating means. On the gyroscope housing a mirror is mounted, in which a sighting is made with the help of ten autocollimating tube which is rigidly joined with a theodolite.



a) b)

Fig. 34. Construction of gyrocompasses: a) with suspension on a spire; 1 – electrodes; 2 – rotor; 3 – liquid; 4 – spire; 5 – tube; 6 – mirror; 7 – autocollimator; b) with suspension on a torsion bar; 1 – rotor; 2 – torsion bar; 3 – mirror; 4 – objective; 5 – semitransparent mirror; 6 – receiver of radiation; 7 – analyzing prism; 8 – tube.

A gyrocompass with suspension on a torsion bar consists of three main parts:

- gyroscope housing;

- photoelectric follow-up system;

- theodolite with scale and reading device.

The gyroscope is suspended on a thin torsion bar. For excluding the influence of torsion moment, arising during the twisting of the torsion bar in the process of oscillations of the gyroscope, on the accuracy of determination of direction of the meridian a continuous turning of the suspension is carried out immediately after shifting of the gyroscope housing with help of a follow-up system.

Characteristics of gyrocompasses differ significantly depending on their design features and principles of construction. Basic characteristics of certain foreign gyrocompasses are cited in Table 7.

Table 7.

Designations	PIM England 1962	'AT USA 1963	"Orientor" USA 1961	"Guitar" USA 1962	Head TK-3 FRG 1963
Error of orientation	1'	1'	30"	20"	20"
Time of orientation, min	15—30	8—10	25	20	30—45

The most accurate of these gyrocompasses — "Orientor," "Guitar," and gyroscopic head for the TK-3 theodolite — are free with torsion suspensions. The gyrocompass "Orientor" has an automatic follow-up system, ensuring that the suspension of the gyroscope housing follows its precessional motion.

CHAPTER VII

SERVOSYSTEMS

§ 1. Assignment and Elements

A servosystem is the name given to an automatic device, intended for reproduction on the output of a certain input value (angle, linear shift, voltage) which changes by an arbitrary law. The servosystem usually reproduces a given value in the absence of a mechanical connection between the assigning and regulated devices.

The area of application of servosystems in instruments for aiming of missiles is quite extensive. They are used in photoelectric goniometers for the measurement of angular mismatch, in devices for following the instrument section in the event of wind rolling of a missile, in polarization and induction synchronous gears for matching the angular position of the receiver with transducer, in devices enabling the suspension of a gyrocompass to follow the precessional motion of a gyroscope, in gyroscopic stabilizers, and in systems for azimuthal turning of the onboard gyroplatform or launching pad together with the missile during fulfillment of concluding operations of aiming.

In Fig. 35 is shown a diagram of a servosystem. It consists of two main parts; regulator and object which is regulated. The regulator serves for comparison of input and output values and the generation of a regulating influence on the regulated object, thus ensuring the equalization of these values. Comparison of input and output quantities is carried out due to the presence of feedback in the servosystem.

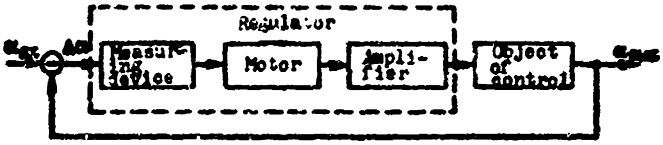


Fig. 35. Diagram of a servosystem.

The value passed to the input of the regulator,

$$\Delta\varepsilon = \varepsilon_{\text{вх}} - \varepsilon_{\text{вых}}$$

is called the mismatch signal. The servosystem operates continuously for elimination of mismatch. The input value can be constant and can change with the flow of time by a definite law or randomly. For example, accidentally a shift of the instrument section during wind rolling of a missile.

Automatic regulator usually consists of three basic elements: measuring device, amplifier-converter, and regulating organ or motor.

The measuring device measures the difference between the input and output values. For this on its input the input value is fed, and on the feedback circuit - output value. The amplifier-converter serves for amplification of the signal in voltage and power and conversion of it from one form to another. It frequently includes modulators and demodulators. The regulating organ serves for exerting the necessary influence on the regulated object. In many servosystems for aiming instruments an electric motor is used as the regulating organ; in gyroscopic devices for this purpose a torque transducer which causes precession of the gyroscope is used.

Transmission of command signal from measuring device to regulating organ and regulated object is done on a circuit of direct communication. Control over the performance of commands is carried out by a feedback circuit which connects the output of the servosystem with its input. Communication between separate elements of the servosystem can be of three forms: electrical, optical, and mechanical. In some servosystems all three forms of communication are used.

§ 2. Basic Properties and Characteristics of Servosystems

In an appraisal of properties of a servosystem type signals are supplied on its input and its properties are determined on the basis of an analysis of the output signal. The most widespread type signals are sinusoidal and unit stepped.

A sinusoidal input signal is determined by the expression

$$\alpha_{\text{вх}} = \alpha_{\text{max.вх}} \cdot \sin(\omega t + \psi_{\text{вх}}),$$

where $\alpha_{\text{max.вх}}$ – amplitude of signal; ω – its frequency; $\psi_{\text{вх}}$ – phase. On the output of the servosystem after a certain time oscillations of output value are established

$$\alpha_{\text{вых}} = \alpha_{\text{max.вых}} \cdot \sin(\omega t + \psi_{\text{вых}}).$$

The frequency of these oscillations is the same as on the input, however, amplitude and phase of these oscillations differ from the amplitude and phase of the input signal. This signal is the natural form of input influence for systems for following the instrument section during wind rolling of a missile.

The unit stepped signal is characterized by an instantaneous increase from zero to a certain constant value. This influence is attained by means of switching on the servosystem when a certain angle of mismatch is present on the input.

In the event of supply of a gradual influence on the input of the system a stabilized value of output quantity will be attained after a specific interval of time. Change of output value following receipt of a stepped influence on the input of the servosystem is called transition process. In a servosystem the transition process can be without overshooting, when during adjustment of the entrance influence the mismatch signal does not change its sign, and with overshooting – in the presence of even one change of sign of mismatch. In Fig. 36 are shown typical characteristics of transition processes which develop in servosystems.

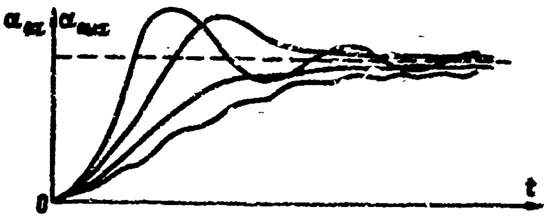


Fig. 36. Characteristics of transition processes.

Basic indices of quality of work of servosystems are:

- stability;

- high speed operation;

- oscillation capacity;

- overshooting;

- accuracy.

A servosystem is called stable, if when it is taken out of a state of equilibrium it again returns to this state. In a stable servosystem the transition process fades with the flow of time, but in unstable it lasts for an indefinite long time. Development of instability in a servosystem promotes an increase of its amplification factor.

High speed operation of a servosystem is characterized by the time during which the transition process in it is practically concluded. Usually the transition process is considered completed, when the output value differs from the constant input influence by no more than 5%.

Oscillation capacity of the system is determined by the number of oscillations appearing in it during transition operating conditions. Usually no more than one or two oscillations is allowed, since a large number of oscillations leads to wear of the mechanical elements of the servosystem.

Overshooting is the name for maximum deflection of amplitude of output value from a constant input influence. Overshooting should not be too great, since with an increase of it considerable dynamic forces can appear in the mechanical elements of the system and in electrical - large voltages which are caused by a large mismatch signal.

In the case of operation of a servosystem in a steady state, when the transition process is finished, the basic index of quality of its work is the accuracy determined by error

$$\Delta\alpha_{\text{уст}} = \alpha_{\text{вх}} - \alpha_{\text{вых}}.$$

Depending upon the operating conditions system errors are distinguished as static and high-speed.

Static error is found in a system, when on its input a constant disturbance is acting. Reasons for it are: dry friction and play in mechanical elements, unbalance of amplifying-conversion devices.

High-speed error appears during a change of input influence with the course of time by a linear law, i.e., with a constant speed. High-speed error increases with an increase in the rate of change of input value. Value of high-speed error is greater than the value of static.

Static and high-speed error decrease with increase of amplification factor of the servosystem. It is necessary, however, to consider that with an increase of amplification factor the system can lose stability.

§ 3. Systems for Following Wind Rolling of a Missile

The system for following the onboard prism in the case of wind rolling of a missile serves to ensure the continuous influence of a light single, reflected from the prism, on the autocollimator. In the absence of such system, if amplitude of oscillations of the missile instrument section becomes equal to the diameter of the objective of the goniometer, the loss of light signal by the goniometer may be observed.

Diagram of a servosystem is depicted in Fig. 37. It includes an autocollimating goniometer, amplifier, motor with tachogenerator, reduction gear, and reflector. The reflector is the adjustable object, and all the remaining elements in their totality constitute the regulator.

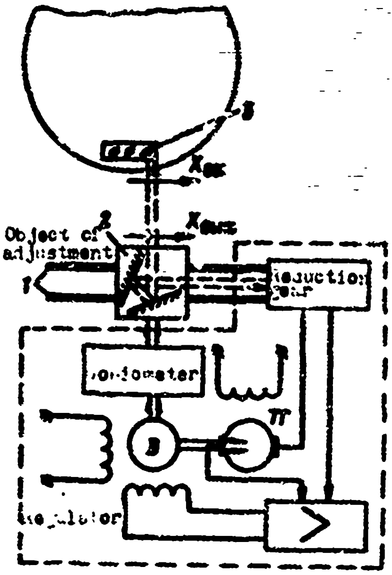


Fig. 37. System for following the rolling of a missile: 1 – guides; 2 – reflector; 3 – control prism.

The tachogenerator [TG] is an electrical machine, producing voltage which is proportional to the angular velocity of rotation of its shift. It is included in the supplementary circuit of negative feedback, which serves for improvement of the quality of the transition process: increase of stability and decrease of oscillation. In the figure electrical connections are designated by solid lines, optical - dotted line, and mechanical - double lines.

Input value of the servosystem is the forward shifting of the onboard prism, and output - shifting of the reflector. The measuring element of the system is a goniometer, which according to the nature of change of light signal on its input evaluates the relative position of onboard prism and reflector and produces an electrical signal which is proportional to the linear displacement of the onboard prism with respect to the reflector. The regulating organ of the system is the motor which moves the reflector on guides.

In the development of systems for following the wind rolling of a missile high requirements are presented for their high-speed operation. The nature of quick operation should ensure the reliable tracking of the onboard prism by the reflector. Frequency of oscillations of missiles can attain units of hertz, and amplitude - tens of centimeters.

Requirements for accuracy of the servosystem are comparatively low, since its maximum permissible error is determined by the diameter of the goniometer objective. Error in tracking has the greatest significance in the middle of the operation zone of the servosystem, since its basic component is speed error, the value of which depends on the rate of change of input disturbance, which has the greatest significance in the middle of the operation zone of the servosystem, since its basic component is speed error, the value of which depends on the rate of change of input disturbance, which has the greatest significance in the middle of the operation zone of the tracking system.

It is necessary to consider that with a low degree of accuracy for the reflector which is tracking the instrument section, part of luminous flux reflected from the prism will not reach the goniometer objective. A periodic change of amplitude of light signal arriving at the goniometer will elicit the appearance of error on the output of the basic channel of the goniometer, in which a mismatch signal develops between the plane of firing and basic plane of stabilization of the missile.

§ 4. Measuring Servosystems

Measuring servosystems are a component part of goniometers which are working under measuring conditions. They make it possible to automatically measure the angle of mismatch between sighting axis of the goniometer and basic plane of stabilization which is fixed by a control prism.

In Fig. 38 are depicted two varieties of such servosystems; in one of them angular turning of sighting axis is done by means of shifting the analyzing prism, and in the second – by slanting the glass plate through which the light rays pass. By turning the plate to this or that side, it is possible to combine the focused light rays on the slot. The arrows in the figures show the direction of shifts of analyzing prism or plate depending on the direction of turning of the control prism.

For determination of the value of measured angular mismatch the goniometers are equipped with angle transducers. An angle transducer can be discrete or continuous. In the first case on its output pulses appear, the quantity of which is proportional to the measured angle. In the second case on the output there will be a constant or alternating voltage, the amplitude of which is proportional to the measured angle. The angle transducer is rigidly joined with the analyzing prism or turning glass plate.

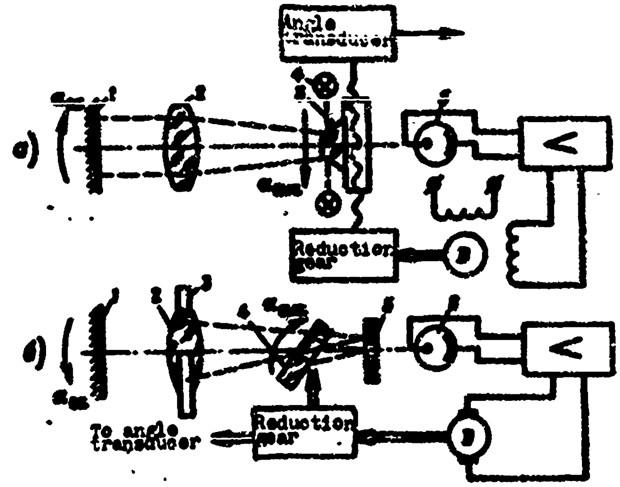


Fig. 38. Measuring servosystems: a) autocollimating goniometer; 1 – control mirror; 2 – objective; 3 – analysing prism; 4 – tube; 5 – receiver of radiation; b) goniometer with external light source; 1 – control mirror; 2 – objective; 3 – tube; 4 – turning plate; 5 – diaphragm; 6 – receiver of radiation.

A measuring servosystem works on a constant disturbance which is assigned on its input. The time which is assigned for adjustment of disturbance is usually sufficiently great, therefore the requirement for a high-speed system is comparatively low.

Very high requirements are presented for the accuracy of the servosystem, since its errors directly affect the error of aiming the missile. Accuracy of measurement of angle depends both on the characteristics of the servosystem and also on the parameters of the angle transducer. For increasing the accuracy of servosystems attempts are being made to increase its amplification factor. Accuracy of the transducer can be increased by improving the quality of its manufacture and by increasing the transmission ratio connecting the shift of the analysing prism with the turning of the transducer.

§ 5. Servosystems of Synchronous Gears

Servosystems in synchronous gears serve for the continuous coordination of angular position of the receiver with the position of the transducer or conversely – transducer with the position of the receiver. During transmission of angular values with the help of synchronous gears the requirements for their servosystems are analogous to the requirements for measuring servosystems: they have to possess high accuracy, but can have a low speed of response. If, however, the receiver of a synchronous gear serves for tracking the angular velocity of a transducer, high requirements can also be presented for the speed of response of the system.

In Fig. 19 the servosystem of a polarization synchronous gear was shown. The measuring device of the servosystem is the receiver, and the regulated object – the body of the receiver together with the elements placed in it.

In the event of angular mismatch between positions of transducer and receiver a controlling signal is produced on the output of the receiver. This signal exerts an influence on the motor, which turns receiver around a vertical axis until coincidence of it with the position of the transducer.

The arrangement of a servosystem of a synchronous gear on rotary transformers was depicted in Fig. 26.

From the rotor of the receiver, which is the measuring element, a mismatch signal is taken which is proportional to the angle between positions of transducer and receiver. After amplification the angle moves to the motor, which turns the receiver around a vertical axis until coincidence with the position of the transducer.

Servosystems are possible in which the controlling signal is fed to the drive of the transducer. In such systems the regulated object is the transducer of the synchronous gear.

§ 6. Servosystems for Turning Missiles and Gyroplatforms

Servosystems for turning a missile or gyroplatform around a vertical axis serve for execution of the concluding operation of azimuthal aiming – combination of the basic plane of stabilization of the missile with the plane of launching.

In Fig. 39 are shown diagrams of servosystems for turning a missile and a gyroplatform. In the first of them the measuring element is a goniometer, working under zero conditions, and the adjustable object – the turning unit of the launching pad together with the missile. A peculiarity of this servosystem is its high power on the output, which is necessary for surmounting the inertia of the great mass of the missile and the large friction moment in the turning device for the launching pad.

Input influence of the servosystem is the azimuthal position of the sighting axis of the goniometer, combined with the plane of firing, and the output value of the system – direction of basic plane of stabilization, fixed by a perpendicular to the control prism.

For improvement of the transition process in the servosystem there is an additional feedback. During development of a servosystem very high requirements are presented for its accuracy: error of adjustment of input value usually does not exceed several angular seconds. During operation of the servosystem no variations of output value are allowed. Requirements for high-speed operation of the system are comparatively low. For decreasing the time expended on aiming, the reduction gear of the servosystem makes it possible to conduct adjustment of input value on two speeds: high and low. At large angular mismatches between position of sighting axis of the goniometer and basic plane of stabilization the adjustment is conducted at a high speed, but upon achievement of an angular mismatch of a specific value the servosystem is switched to a low speed of adjustment.

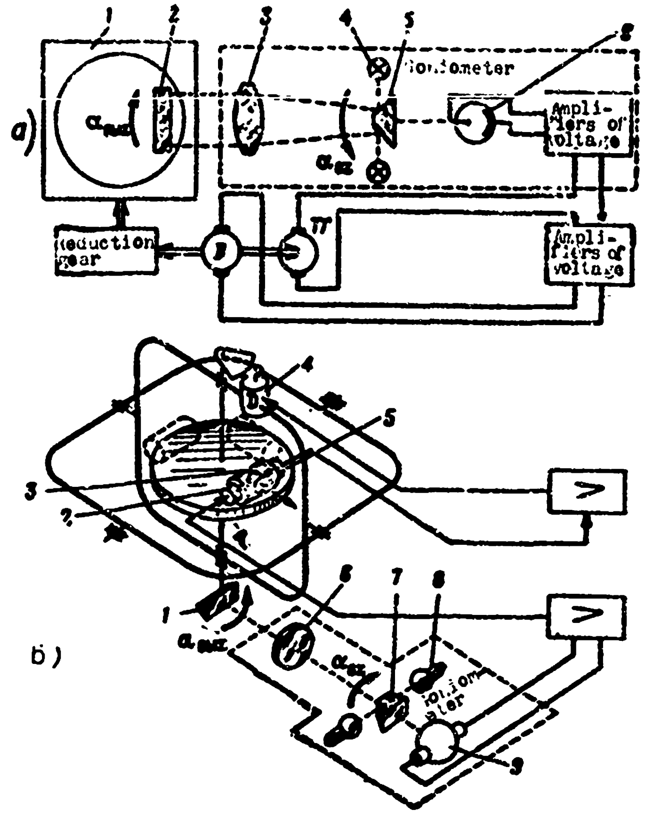


Fig. 39. Systems for turning missiles and gyroplatforms: a) system for turning a missile: 1 – launching pad; 2 – control prism; 3 – objective; 4 – tube; 5 – analyzing prism; 6 – receiver of radiation; b) system for turning the gyroplatform: 1 – control prism; 2 – transducer of moment; 3 – gyroscope; 4 – motor; 5 – transducer for angle of precession; 6 – objective; 7 – analyzing prism; 8 – tube; 9 – receiver of radiation.

In the servosystem for turning the gyroplatform a goniometer working under zero conditions is also used as the measuring device. The regulated object of the system is the gyro-stabilized platform on which the control prism is mounted.

The luminous flux, coming out of the objective of the goniometer, is reflected from control prism and is analyzed in the goniomenter. On the basis of the analysis of the light signal in the goniometer an electrical mismatch signal is developed and passed to the gyroplatform.

This signal is fed to the torque transducer of the roll gyroscope and causes the precession of the gyroplatform around a vertical axis. Adjustment of mismatch is ceased when the perpendicular to the control prism coincides with the sighting axis of the goniometer.

Mismatch signal produced by the goniometer can be fed directly to the motor for azimuthal turning of the gyroplatform. However, in the supports of the gyroscope a gyroscopic moment will appear which strives to preserve the initial position of the axis of its rotation. The presence of the resistant moment renders an unfavorable influence on accuracy of adjustment of input value by the servosystem.

CHAPTER VII

MISSILE AIMING SYSTEMS USING EXTERNAL INFORMATION

§ 1. Vertical Positioning of Missiles

Vertical positioning of missiles is accomplished with the help of jacks for the launching pad. For controlling the position of longitudinal axis of the missile with respect to vertical two theodolites are used which are mounted at a certain distance from the launching pad. The angle between planes of sighting of the theodolites in the direction of the missile compresses 90°. Prior to vertical positioning of the missile both theodolites are thoroughly established horizontally with the help of levels.

On the body of the missile there are referred points, the line between which is parallel to the longitudinal axis of the missile. During vertical positioning of a missile at night the reference points are illuminated.

Each of the theodolites in turn sight at first on the lower, and then on the upper reference point. If the upper reference point deviates from the vertical filament of the crosshairs of the theodolite retide which is combined with the lower point, the body of the missile is inclined to corresponding side with the help of launching-pad jacks. Then the same operation is carried out with the help of the other theodolite. The missile will be set in a vertical position, if the reference points in the field of vision of both theodolites coincide with vertical the filaments on the crosshairs of their reticles.

The basic components of error in the vertical positioning of a missile are:

- error due to inaccuracy in the horizontal positioning of the theodolite;

- error in sighting with the theodolite on the reference point.

Error in establishing the reference points on the body of the missile enters completely in an error of vertical positioning. Error of vertical positioning of a missile due to inaccuracy of horizontal positioning of the theodolite equals

$$\Delta\beta_1 = \sin B \cdot \Delta\beta, \qquad (43)$$

where B – angle between direction of sighting on reference point and direction of slant of the theodolite limb; $\Delta\beta$ – error of horizontal positioning. Influence of sighting error on accuracy of vertical positioning of a missile is determined by the formula

$$\Delta\beta_2 = \frac{\Delta\alpha}{\sin\varepsilon}, \qquad (44)$$

where ε – angle of sight of upper reference point; $\Delta\alpha$ – error of sighting with theodolite. From formula (44) it follows that the position of the theodolites should not be removed from the launching pad by a great distance, since by this the accuracy of vertical positioning is lowered.

Requirements for accuracy in the vertical positioning of missiles are determined by the influence of errors of vertical positioning on the accuracy of azimuthal aiming, and also by the necessity of ensuring a stable position for the missile on the lauching pad in the event of wind rolling. Error in the vertical positioning of a missile usually comprises several angular minutes.

§ 2. Systems for Aiming Missiles During Launching from Ground Launchers

During launching of missiles from ground launchers two types of aiming systems are used: single-channel and two-channel.

An example of a single-channel system is a system for aiming the "Saturn" missile, the layout of which is depicted in Fig. 40. It includes the following elements: autocollimating goniometer, tracking reflector with drive, prism, fixing the oriented geodetic direction, amplifying-conversion block, onboard control prism, drive for gyrostabilized platform, television transmitting installation, and control unit for aiming system.

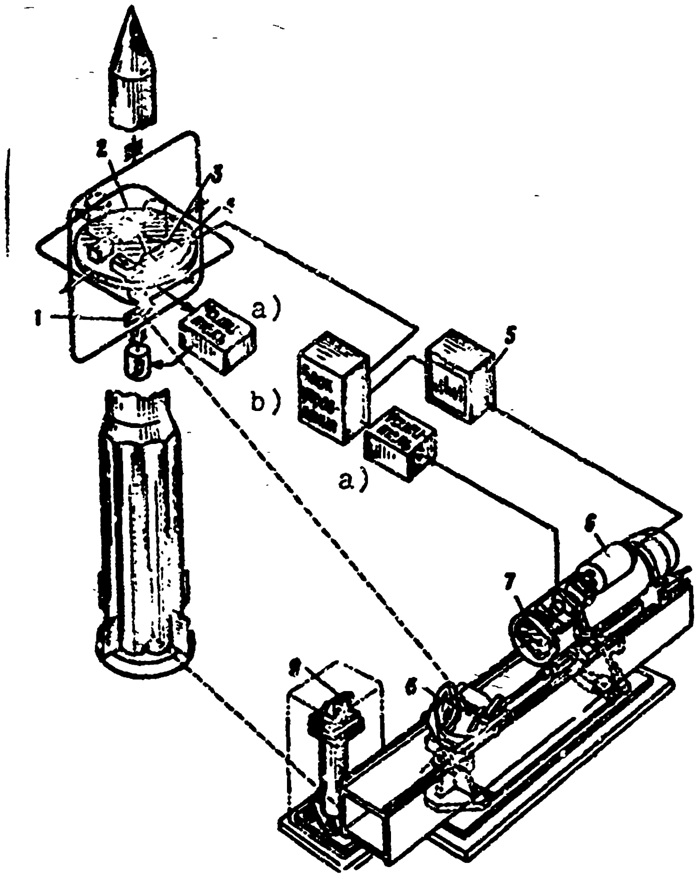


Fig. 40. Arrangement of the system for aiming the "Saturn" missile: 1 – control prism; 2 – transducer for precession angle; 3 – gyroscope; 4 – torque transducer; 5 – television receiver; 6 – television transmitter; 7 – objective; 8 – reflector; 9 – prism.
KEY: a) Amplifier; b) Control unit.

The autocollimating goniometer together with the tracking reflector are mounted on a fixed base at a distance of 300 m from the launcher. Before aiming geodetic tying in of the position of the sighting axis is carried out. For periodic positional checking of the goniometer a special prism is used.

With the help of the tracking reflector the light rays coming out of the objective of the goniometer turn evenly by 90° and at an angle of 25° to the horizon are directed to the onboard control prism. On the basis of an analysis of the luminous flux reflected from the prism a controlling signal is produced with is passed on to the drive for turning the gyrostabilized platform for azimuth. During adjustment of this controlling signal the onboard prism occupies a position at which a perpendicular to it will be perpendicular to the sighting axis of the goniometer.

The onboard control prism does not have a fixed position relative to the basic plane of stabilization of the missile. It is secured on the stabilized base of the gyroplatform in a suspension which can revolve relative to the gyroplatform within limits of 360°. By changing the position of the prism relative to the basic plane of stabilization of the missile, it is possible to change the direction of launch at a fixed position of sighting axis of the goniometer.

For controlling the operation of the aiming system there is a special control unit. From this block commands are given to the tracking reflector during the initial gripping of the onboard prism by the aiming system. A lock-on signal is produced in the goniometer and fed to the control unit. For controlling the operation of the aiming system under conditions of pickup of the onboard prism and under conditions of adjustment of mismatch signal by the servosystem for turning the gyroplatform there is a television installation. Its transmitting camera is placed on the goniometer, and into it is fed a share of the light mismatch signal produced by the goniometer. In the goniometer it is also foreseen to have the direct visual control of accuracy of aiming by the operator. With this goal part of luminous flux from the goniometer is directed to a sighting device.

A two-channel system of aiming, which is shown in Fig. 41, includes two autocollimating goniometers and two servosystems, one of which serves for turning the missile, and the other – the gyro-stabialized platform.

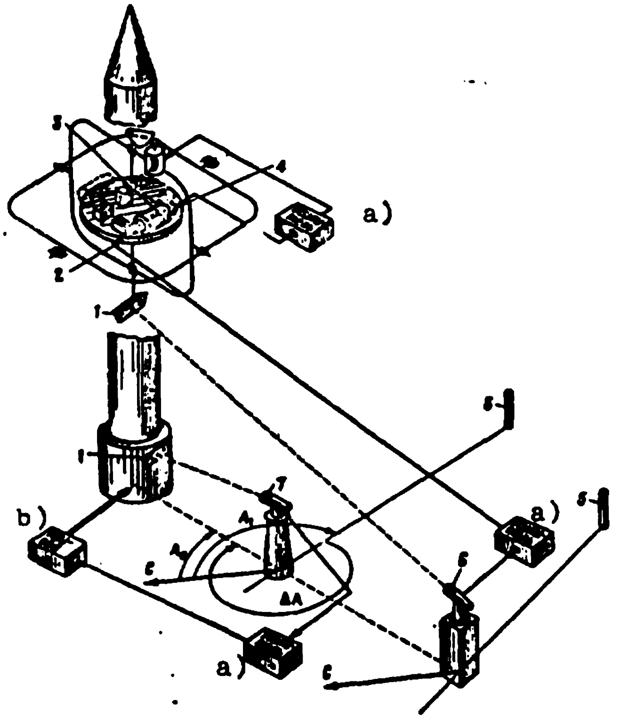


Fig. 41. Two-channel system of aiming: 1 – control prism; 2 – torque transducer; 3 – gyroscope; 4 – transducer for angle of precession; 5 – oriented point; 6 – distant goniometer; 7 – near goniometer.
KEY: a) Amplifier; b) Drive

The goniometer of the first servosystem is mounted in direct proximity to the launching pad. Sighting with this goniometer is carried out by means of a control prism secured on the rotating section of the launching pad. Mismatch signal, produced by the near goniometer, is fed to the drive for turning the launching pad together with the missile.

The assignment of the near goniometer is the coarse aiming of the missile, thus, ensuring the work of the distant goniometer. It also ensures the reaiming of the missile on another target. For this on the launching pad there are two control prisms: one corresponds to the azimuth of firing on the main target, and the second - on an additional one.

The distant goniometer, included in the servosystem for fine aiming of the missile, is mounted at a distance of 130-150 m from the launching pad. The luminous flux, radiated by this goniometer, is directed to the onboard control prism which is joined to the gyrostabilized platform. The mismatch signal, produced by the goniometer, after amplification is fed to the drive for turning the gyroplatform, and it turns around in azimuth until coincidence of the basic plane of stabilization of the missile with the plane of firing.

Prior to aiming the missile the near and distant goniometers are mounted in such a way that their sighting axes coincide with the plane of firing. For their orientation azimuths of launch A_0 and oriented geodetic direction A_1 are used. Sighting angle (angle between directions of plane of firing and on the oriented point) is determined by the formula

$$\Delta A = A_0 - A_1. \tag{45}$$

If the value of the sighting angle obtained here is negative, then it is increased by 360°.

A peculiarity of the examined aiming system is the dependence of position of the goniometer on the launching azimuth of the missile. The exact position of the goniometer is selected in such a way that the direction of its sighting axis in the case of its coincidence with the plane of firing simultaneously coincides with the direction to the control prism. This means that the plane of firing should pass through the exact position of the launching pad and the goniometer. If the direction of firing is changed, then the position of the goniometer should be shifted along the arc of the circumference.

This deficiency is lacking in the aiming system for the "Saturn" missile, since for changing the direction of firing in this missile it is only necessary to turn the control prism relative to the gyroplatform.

§ 3. Aiming of Missiles During Launching from Mobile Launchers

For aiming the "Minuteman" missile during launching from a railroad launcher an automatic system of aiming has been developed which includes the following elements:

- gyroscopic compass;
- stabilized platform of gyrocompass;
- polarization synchronous gear;
- autocollimating goniometer;
- stabilized platform of goniometer;
- control unit.

A diagram of the distribution of the basic elements of the aiming system is depicted in Fig. 42.

The gyroscopic compass is placed under special protective cap, mounted on a stabilized platform at the launching pad. Under the same cap there is also an operator, working with the gyrocompass for the determination of direction of the meridian prior to aiming.

Operation of the entire system of aiming is controlled with help of instruments mounted on a control panel. On it there are indicators, signaling relative to the exactness of elements of the aiming system, and scales on which the reading of angles is carried out with the help of the gyroscopic compass.

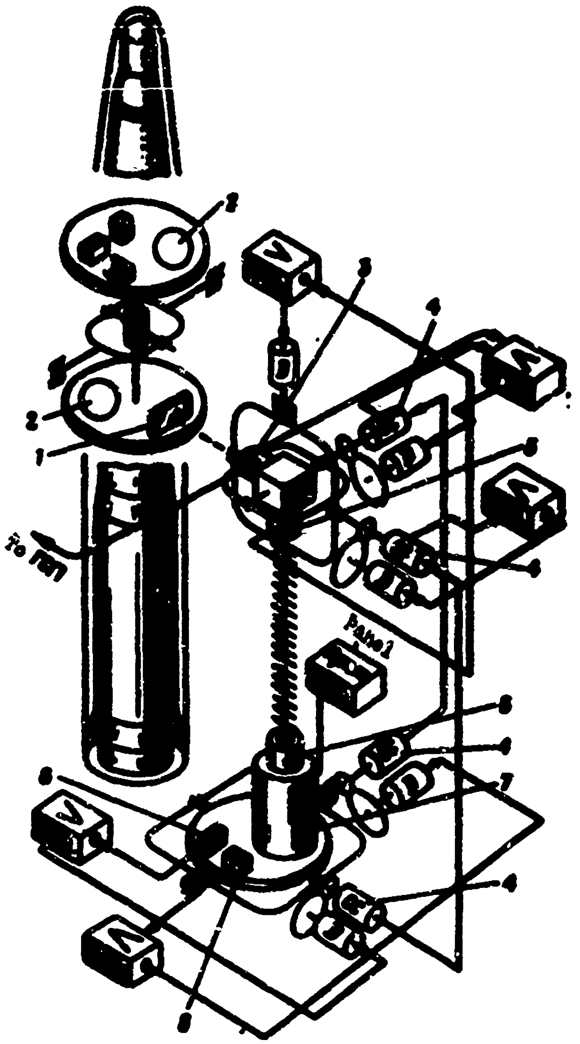


Fig. 42. Layout of the system for aiming a "Minuteman" missile during launching from a railroad launcher: 1 – control mirror; 2 – spherical gyroscope; 3 – goniometer; 4 – selsyn; 5 – receiver of synchronous gear; 6 – transducer of synchronous gear; 7 – gyrocompass; 8 – vertical transducer.
Designation: ГСП = GSP = gyro-stabilized platform.

For transmission of direction of launch from the gyrocompass to the goniometer, which is mounted at the instrument section of the missile on a container, there is a polarization synchronous gear. The transducer of the synchronous gear is mounted on the turning unit of the gyrocompass. After the direction of meridian and azimuth for launching the missile are determined the transducer is oriented manually by the operator. The information carrier about azimuth of missile launch is a polarized and modulated bundle of light. The receiver of the synchronous gear is mounted at a height of 14 m above the level of the transducer. It is rigidly fastened to the goniometer, therefore after coincidence of the position of the receiver with the azimuthal position of the transducer of the synchronous gear the sighting axis of the goniometer is established in the plane for firing.

The goniometer together with the receiver of the synchronous gear are mounted on a stabilized platform, which is secured in a gimbal suspension. The platform can be rotated in the gimbal suspension for azimuth within limits of ±5° and for angle of sight within limits of ±3°.

The platform of the goniometer is covered from above with a housing. In the housing there are three windows covered by protective glass: one is directed downwards and serves for transmission of the light bundle from the transducer of the polarization synchronous gear, the second is horizontal and is intended for sighting with the goniometer the control mirror on the onboard gyrostabilized platform, and the third is directed downwards at an angle of 45° to the horizon; through it is conducted sighting with the autocollimating theodolite on the prism, secured on the goniometer, during the checking of accuracy of operation of the aiming system.

The aiming system includes several autonomous and mutually connected with each other servosystems:

- system for turning the suspension of gyrocompass after the precessional movement of its gyroscope housing;

- system for horizontal positioning of gyrocompass platform;

- servosystem of the polarization synchronous gear;

- servosystem for horizontal positioning of stabilized platform of the goniometer with the help of an induction synchronous gear, connecting it with the platform of the gyroscopic compass;

- servosystem for horizontal positioning of the goniometer platform by controlling commands produced by the goniometer;

- servosystem for turning the onboard gyrostabilized platform for azimuth.

The gyroscopic compass used in the aiming system has the torsion suspension of gyroscope housing. The gyroscope housing is placed in a vessel with liquid, which decreases the tension of torsion and ensures to a certain degree the damping of vibrations, appearing during the operation of various launcher units. For excluding the influence of torsion moment on the accuracy of the gyrocompass there is a servosystem revolving the suspension following precession of the gyroscope housing. The period of precessional movement of the axis of the gyrocompass comprises 8 minutes.

Before determination of the direction of the meridian the axis of the gyrocompass is preliminarily oriented roughly with respect to it with an error of around 5°. For such an orientation the direction of the railroad line is used. Its azimuth is determined on a map.

For horizontal positioning of the gyroscopic compass and elimination of the influence of mechanical oscillations of the launcher on its operation, it is mounted on a stabilized base. Transducers for the stabilization system are two accelerometers, the axes of which are established in mutually perpendicular planes. Mismatch signals are fed to the drives for horizontal positioning based on the corresponding axes of the platform.

In a polarization synchronous gear electrical modulation of light signal is used with the help of a modulator mounted in a transducer. Analysis of the light signal in the receiver is carried out with the help of a Wollaston prism, dividing the luminous flux into two parts, each of which is percieved by a photoelectric receiver. If the angle between the axes of polarization of the light signal by the transducer and the axes of the Wollaston prism equals 45°, the light signals incident on the receiver of radiation are equal to each other and the mismatch signal on the output of the amplifier of the synchronous gear equals zero. Upon disruption of the shown condition a mismatch signal appears which exerts an influence on the azimuthal drive of the stabilized platform of the goniometer. When the receiver of the synchronous gear arrives at a coordinated position with the transducer, the sighting axis of the goniometer coincides with the direction of the plane of launching.

For the preliminary coarse horizontal positioning of the goniometer platform there is an induction synchronous gear. The transducer of this synchronous gear is mounted on the stabilized base of the gyrocompass, and the receiver – on the platform of the goniometer. If the platform is not horizontal, then between the positions of the transducer and the receiver of the synchronous gear an angular mismatch appears. Here the mismatch signal from the receiver is fed to the drive for horizontal positioning of the platform.

For precise horizontal positioning of the stabilized platform of the goniometer there is a servosystem, the measuring device of which is a goniometer. The autocollimating goniometer works on a polarized light signal. It produces a mismatch signal between the sighting axis and a perpendicular to the control mirror in two planes: vertical and horizontal.

The mirror is mounted on the stabilized section of the gyroplatform. It has an inner gimbal suspension, ensuring its turning on an azimuth within the limits of ±70°. On the gyroplatform two spherical gyroscopes with air suspension are mounted.

Mismatch signal, produced by goniometer in a vertical plane, is fed to the drive for horizontal positioning of the platform of the goniometer. The operation of this servosystem ensures coincidence of the position of stabilized platform of the goniometer with the position of the onboard gyrostabilized platform with respect to the plane of the horizon. The necessity for precise horizontal positioning of the goniometer platform is caused by the influence of errors of horizontal positioning on the accuracy of the polarization synchronous gear. Error of deflection of the goniometer platform from the position of the onboard gyroplatform does not exceed 10".

Turning of the onboard gyrostabilized platform for azimuth up to coincidence of the basic plane of stabilization with the plane of firing is carried out by a servosystem, the measuring element of which is also a goniometer. Here the mismatch signal produced by the goniometer for azimuth is used.

The mismatch signal, produced by goniometer, after amplification is fed to the drive for azimuthal turning the onboard platform. Maximum angle of rotation of the onboard platform based on signal from the goniometer comprises 60".

§ 4. Aiming of Missiles During Launching from Silo Launchers

The system for aiming the "Minuteman" missile when it is launched from a silo launcher is organically connected with the system for missile control and the ground checking-launching equipment.

A peculiarity of the "Minuteman" missile is the fact that when it is located in the silo the gyrostabilized platform is found in a working condition. This ensures a very small loss of time for preparation of the missile for launching (around 30 seconds). The high degree of reliability during the continuous operation of the gyroplatform is ensured by its construction on spherical gyroscopes, the rotors of which during rotation do not have mechanical contact with the stator, therefore their wear is extremely insignificant. Mounted on board the missile is a digital computer (TsVM), which, in addition to solving problems of flight control of the missile, fulfills a number of operations for preparing the missile for launching, including aiming the missile.

The layout for aiming the missile is depicted in Fig. 43.

The measuring element of the aiming system is an autocollimating goniometer, mounted in the upper equipment level of the silo on a special annular rail. The position of the goniometer on the annular rail depends on the azimuth of firing. Aiming of the missile is done in two stages: first it is turned to the approximate position with the help of the turning device on the launching pad, then – aiming is carried out by turning the onboard gyrostabilized platform for azimuth.

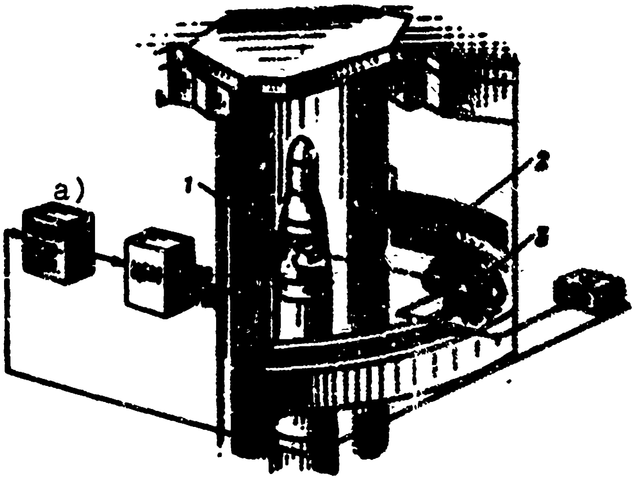


Fig. 43. Layout for aiming the "Minuteman" missile during launching from a silo: 1 – control mirror; 2 – annular rail; 3 – goniometer.
KEY: a) Converter.

Azimuth of sighting axis of goniometer is determined by means of transmission of directions from a geodetic grid or from astronomical observations. Sighting with the theodolite during geodetic tying in of the goniometer is done through the hatch in the roof of the silo.

When the goniometer is switched on it generates a modulated light signal, which passes through the hatches in the silo tube and the missile container and reaches the control mirror secured on the onboard gyroplatform. The light ray reflected from control mirror is analyzed by goniometer and on the basis of this the mismatch signal is produced. A mismatch signal different from zero appears only in case of azimuthal departure of the working gyrostabilized platform.

After amplification the mismatch signal is fed to the signal converter. In the converter it is converted into a digital form and is fed to the onboard digital computer, which continuously corrects the position of the gyrostabilized platform for azimuth. Thus the signal of corrections, which is produced by the goniometer, ensures coincidence of the perpendicular to the control mirror with the sighting axis of the goniometer.

During input of flight assignment into the onboard computer the possibility of reaiming the missile on an additional target is anticipated. Reaiming of the missile can be carried out on command from the control room. Reaiming of a missile is carried out by means of turning the gyroplatform on a specific angle from the initial direction. Control of turning of the platform is carried out with the help of discrete angle transducers located on the axes of stabilization of the gyroplatform. Signals, produced by the transducers, are fed to the digital computer.

The possibility of reaiming the missile on one of many targets is limited by the volume of target information embodied in the memory of the digital computer and the maximum permissible angle of turning the gyroplatform for azimuth. This angle of turning for the gyroplatform used on board the "Minuteman" missile, as was already stated, comprises ±70°. If the required deflection shift of the gyrostabilized platform onto a new target exceeds the stated angle, remote-control reaiming of the missile becomes impossible. Reaiming in this case requires additional turning of the missile in the silo, which can be carried out by special command.

§ 5. Aiming of Missiles During Launching from Submarines

The source of information concerning the position of the local vertical and direction of the meridian which is necessary for aiming a missile, is the gyroscopic device in the navigation system of the submarine. The gyroscopic device can work under conditions of a gyrocompass and triaxial gyrostabilizer, therefore the stabilized base of the navigational system maintains not only a horizontal position, but is oriented with a specific accuracy relative to the direction of the meridian.

The most complex problem arising during the aiming of missiles prior to their launching from a submarine is the transmission of oriented directions for three axes from the gyroscopic device of the navigation system to the gyrostabilized platform of the missile. A simpler problem is turning the gyroplatform into the plane of launching from a known azimuthal position.

Orientation of the onboard gyroscopic platform relative to three axes of coordinates for the "Polaris" missile is carried out with the help of an induction synchronous gear, the transducers of which are set on the axes of the stabilized platform of the navigational device, and the receivers – on the axes of stabilization of the onboard gyroplatform. After coordination of the receivers of all synchronous gears with their transducers the onboard gyroplatform will take a horizontal position, and its azimuthal position will correspond to the azimuthal orientation of the platform of the navigational device.

A deficiency of this principle of transmission of directions to the onboard gyroplatform is low accuracy due to the influence on it of deformations of the hull of the submarine when it rolls. Deformation of the hull of the submarine leads to angular mismatch of the axes of the onboard gyroplatform relative to the analogous axes of the stabilized platform of the navigational device. These angular mismatches do not cause the appearance of signals on the output of the transducers of the induction synchronous gear, since their rotors and stators are turning on the same angle. Thus angular deformations of the hull of a submarine enter fully into the error of aiming a missile.

For eliminating the influence of angular deformations of the submarine hull on the accuracy of aiming in addition to the induction synchronous gear a photoelectrical synchronous gear has been developed. Its principle of action can be comprehended from the diagram in Fig. 44.

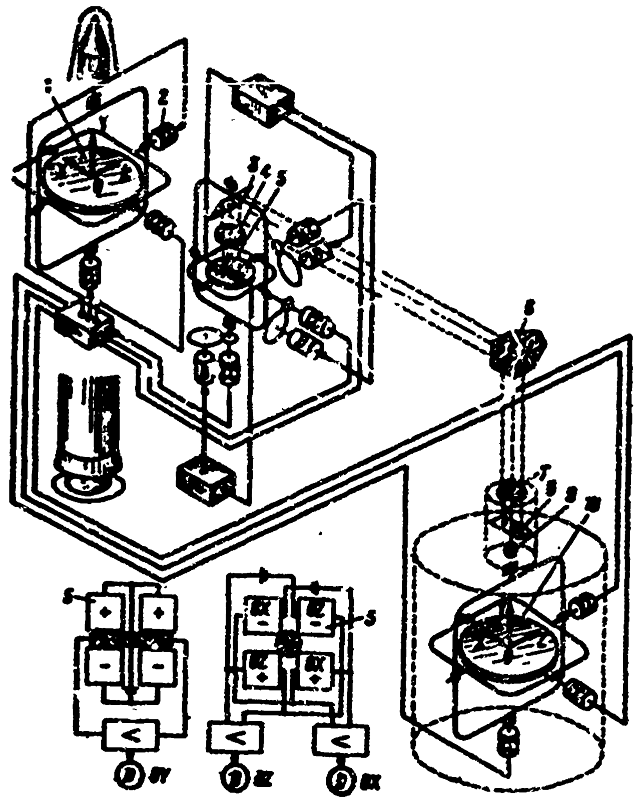


Fig. 44. Arrangement for aiming a missile during launching from a submarine: 1 – onboard gyroplatform; 2 – selsyn; 3 – mirror; 4 – objective; 5 – receivers of radiation; 6 – pentaprism; 7 – objective; 8 – diaphragm; 9 – tube; 10 – gyroplatform of navigational device.

The aiming system in this case consists of the following elements:

- induction transducers of synchronous gears;
- amplifier;
- induction receivers of synchronous gears;
- transducer of photoelectrical synchronous gear,
- prism reflector;
- receiver of photoelectrical synchronous gear.

We already examined the work of the induction synchronous gear during the aiming of missiles; we now will examine the operation of a photoelectric synchronous gear. Its transducer is rigidly joined with the body of the stabilized platform of the navigational system. It consists of a light source, diaphragm, and collimator. In the diaphragm there are two openings: one in the form of a circle of small diameter, and the other in the form of a thin slot. After passing these openings light rays emerge from the collimator in the form of two adjacent parallel bundles.

Secured rigidly above the navigational device is a pentaprism, turning the light rays coming from the collimator exactly by 90°. In connection with the fact that the navigational device and prism are located on one vertical, deformations of the submarine hull do not exert an influence on the path of the rays after passing the prism.

The reciver of the photoelectric synchronous is fastened rigidly to the body of the missile. It is mounted in a gimbal suspension, on each of the axes of which stand the motors of the servosystem and transducers of the induction synchronous gear.

The receiver of the synchronous gear consists of the following elements:

- mirror;
- objective;
- two cross-shaped photoelectric receivers of radiation;
- three amplifiers.

The mirror directs light rays downwards onto the objective, which focuses them on the cross-shaped receivers of radiation. On one of the receivers is construced the image of circular opening, and on the other – a slot.

In case of mismatch of the receiver of the photoelectric synchronous gear with the transducer for angle of pitch or yawing the image of the circular opening is displaced from center and falls on one of the four (or simultaneously on two) receivers of radiation. Receivers of radiation are included in pairs on the input of two amplifiers of photocurrent on a balanced circuit, therefore on the output of the amplifiers mismatch signals appear, the polarity of which corresponds to the sign of angular mismatch in pitch or yawing. This signal is fed to the motors, mounted on the axes of the gimbal suspension of the receiver, which turn it up to coincidence with the transducer.

In the case of mismatch between receiver and the transducer for azimuth (for angle of bank of the missile) the mismatch signal is produced by the second cross-shaped receiver, on which the image of the slot of the transducer of the synchronous gear is constructed. Forward shifting of the image of the slot over the surface of the cross-shaped receiver, which develops in the case of angular mismatch between receiver and transducer of the synchronous gear for angles of pitch and yawing, does not cause unbalance of the bridge, including all four receivers of radiation. In the case of angular mismatch between the receiver and the azimuth transducer the image of the slot is turned relative to the vertical axis and causes the appearance of a signal on the output of the bridge. After amplification this signal moves to the motor for turning the receiver of the synchronous gear for azimuth.

With the turning of the axes of the gimbal suspension of the receiver of the photoelectric synchronous gear the additonal (correcting) transducer of the induction synchronous gear which are mounted on them are rotated. Mismatch signals produced by them are fed to an amplifier. In the amplifier these correcting signals are combined with the basic mismatch signals produced by the transducers of the induction synchronous gear which are mounted in the navigational system of submarine. Total signals are fed to the receivers of the induction synchronous gear which are mounted on the axes of the onboard gyroplatform. After adjustment, by the motor for stabilization of the onboard gyroplatform, of mismatches produced by these receivers, the axes of the onboard gyroplatform will occupy a position parallel to the analogous axes of the gyroplatform of the navigational system. Additional relative angular turns of their axes due to deformation of the submarine hull will also be considered.

CHAPTER IX

MISSILE AIMING SYSTEMS USING ONBOARD DEVICES

§ 1. Principles of Aiming when Using Onboard Devices

For orientation of an onboard gyroplatform using the means which are located onboard the missile it is necessary to have two initial directions, which is due to the fact that it is necessary to orient the platform both relative to the plane of the horizon and also in terms of azimuth.

As initial directions it is possible to use:

- direction of acceleration of force of gravity;
- direction of axis of rotation of earth;
- direction to celestial bodies.

The angle between the pair of directions, utilized as initial for aiming, should be sufficiently large; with a decrease of it there is an increase in the error of aiming. Therefore in high latitudes it is impossible to use directions of acceleration due to gravity and axis of rotation of the earth for aiming of missiles.

Depending on the type of devices used for fixing initial directions, the systems of orientation of gyroplatforms are divided into inertial and astronomical. In inertial systems accelerometers and gyroscopes are used for determination of direction of acceleration due to gravity and axis of rotation of the earth. In astronomical systems of orientation photoelectric telescopes which fix direction on celestial bodies are used.

Orientation of a gyroplatform by using inertial devices can be carried out both prior to launching the missile and also in flight. Orientation using photoelectric telescopes is done in flight, when the missile is at a high altitude and atmospheric disturbances do not exert a significant influence on the work of telescopes.

§ 2. Horizontal Positioning of the Gyroplatform

Horizontal positioning of the gyroplatform is carried out automatically by servosystems for reducing it relative to horizontal axes. Let us consider the principle of action of a system for horizontal positioning (Fig. 4). It includes two autonomous servosystems. The transducers here are accelerometers, which are mounted on the stabilized base of the gyroplatform and produce electrical signals, depending on the position of the gyroplatform relative to the direction of acceleration due to gravity. Sometimes the accuracy of accelerometers utilized in missile control systems is not sufficient for horizontal positioning of the gyroplatform with the necessary accuracy. In these cases on the gyrostabilized platform transducers of vertical are mounted. They are of the liquid level type and possess a high degree of sensitivity and accuracy.

Principle of action of both channels of the system for horizontal positioning is identical. As soon as deviation of the platform from horizontal plane on one of the axes occurs, a mismatch signal is taken from the corresponding transducer. After amplification it is fed to the tongue transducer of one of gyroscopes. The gyroscope together with the platform starts to precess, thus eliminating the mismatch between the plane of the horizon and the platform.

Horizontal positioning of gyroplatforms prior to launching of missiles is also carried out during the aiming of missiles when external information is used (oriented geodetic directions).

§ 3. Azimuthal Aiming Using the Gyrocompass Method

Azimuthal aiming of a missile can be carried out with the help of an onboard gyroscopic compass mounted on the gyroplatform. However, installation of additional elements on the gyrostabilized platform is extremely undesirable. It is more rational to ensure the operation, under conditions of a gyrocompass, of the onboard gyroscopes in the system for controlling the movement of the missile.

For determination of direction of the meridian it is possible to use a conventional triaxial gyrostabilized platform. If the systems of horizontal and azimuthal correction are disconnected then due to rotation of the earth a visible drift of the gyroplatform will be observed relative to the starting system of coordinates which is connected with the earth.

Components of rotation of the earth on three axes of coordinates are equal to:

$$\omega_x = \Omega_{\text{з}} \cdot \cos\varphi \cdot \cos A; \tag{46}$$

$$\omega_y = \Omega_{\text{з}} \cdot \sin\varphi; \tag{47}$$

$$\omega_z = \Omega_{\text{з}} \cdot \cos\varphi \cdot \sin A, \tag{48}$$

where A — azimuth of position of basic plane of stabilization of the missile. Apparent angular velocities of drifts of the gyroplatform can be measured and given to a computer, which determines the azimuth of the basic plane of stabilization.

However, this method of determination of direction of meridian possesses an extremely low degree of accuracy. Its accuracy low is caused by influence of moments of friction in the axes of the gyroplatform on its drifts. Besides this the problem of creation of high-precision transducers of angular velocities of platform drift is very difficult.

Azimuthal orientation of a gyroplatform with the use of inertial transducers is also possible during the flight of a missile. For this purpose it is necessary to preliminarily compare calculated and measured values of components of missile velocities in a horizontal plane. The calculation formula for determination of azimuthal correction in this case has the following form [8]:

$$\Delta A=-\frac{1+k}{R_0}\cdot\frac{(V_{zp}-V_{zи})\omega_x+(V_{xp}-V_{xи})\omega_z}{\omega_x^2+\omega_z^2}, \tag{49}$$

where k - certain coefficient, constant for a given gyrostabilized platform; $V_{xи}$, $V_{zи}$ - measured velocities; V_{xp}, V_{zp} - calculated velocities of missile.

With an increase of latitude of the missile site there is a decrease in horizontal components of angular velocity of rotation of the earth ω_x and ω_z, therefore error of determination of direction of meridian by the examined method increases.

Method of orientation of gyrostabilized platform with use of the given formula amounts to the following. Prior to launching the missile the gyroplatform is established horizontally and oriented roughly relative to the direction of the plane of launching with an accuracy of up to several degrees. Then with help of the onboard computer the azimuthal correction of orientation of the gyroplatform is determined. After that the gyroplatform is turned on azimuth up to coincidence of the basic plane of stabilization of the missile with the plane of firing.

§ 4. Astronomical Method for Orientation of Gyroplatform

In the astronomical method of orientation one or two photoelectric telescopes are mounted on the gyrostabilized platform. These determine the direction to one or two stars. If it is necessary to orient the gyroplatform only for azimuth, then for this it is sufficient to determine the direction to one star. In order to ensure orientation of the gyroplatform relative to three axes, it is necessary to have two telescopes or to sight in turn with one telescope on two stars.

In Fig. 45 a diagram is given of a gyroplatform with a photoelectric telescope mounted on it. It has two drives, ensuring the turning of the sighting axis relative to the stabilized base of the gyroplatform. On each of the axes of rotation of the telescope induction angular transducers are mounted, and with the help of these the orientation of its sighting axis relative to the gyroplatform is determined.

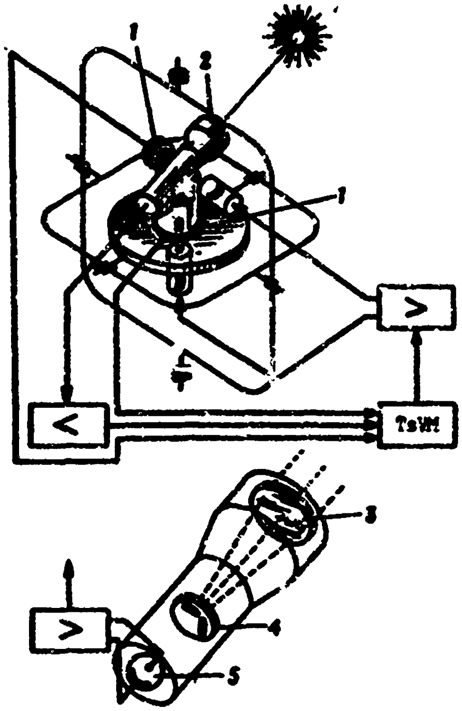


Fig. 45. Astronomical system of aiming: 1 – angular transducer; 2 – telescope; 3 – objective; 4 – diaphragm; 5 – photomultiplier. TsVM = Digital computer.

The telescope consists of an objective, an analyzer in the form of a diaphragm with two perpendicular narrow slots, and a photomultiplier. During shifting of the sighting axis of the telescope in space on a specific program the luminous flux from a star falls through the slot onto the photomultiplier and a signal appears on its output. It is fed to the input of the digital computer, with help of which the azimuth and angle of sight of the star are determined.

Shifting of the telescope is done first for azimuth and then for angle of sight.

In order to ensure the search for stars, in the body of the missile there should be hatches covered with protective glass. A study of density of location of stars showed that two hatches for both directions with angular dimensions of 45°, and the centers of which are dispersed by 60°, ensure the tracking of any two stars at any time of the day and at any point on earth.

For decreasing the sector of the celestial sphere in which the search for a star is carried out, the gyroplatform prior to launching of the missile should be oriented roughly relative to the plane of the horizon and for azimuth. Such an orientation can be carried out with the help of inertial elements of the system for controlling the movement of the missile.

The memory of the onboard computer contains a stellar program containing only star of great brightness. The sensitivity of the telescope also ensures detection of only stars of great brightness. This facilitates their search by the telescope and excludes the possibility of capturing stars which are not in the stellar program. Furthermore, in order to avoid a false response by the telescope and to increase the accuracy of determination of angular coordinates of star, several measurements are made. Results of the measurements are averaged out

For each of the stars found in the program, ahead of time a calculation is made of azimuth and angle of sight, determined relative to the calculated position of the axes of the inertial system of coordinates.

The astronomical system of orientation is switched on only at high altitudes, when atmospheric disturbances will not exert an influence on the functioning of the photoelectric theodolite. Switching on is done on a command issued by the onboard computer.

For orientation of the platform it is necessary to know three angular values: azimuth and angle of sight of one star and angle of sight (or azimuth) of another star. On the basis of these three angles deviations of all three axes of the gyrostabilized platform from their calculated positions are determined. Errors in the orientation of axes of gyroplatform obtained here are small, therefore for calculation of correcting commands to be passed onto the stabilizing motors of the platform it is possible to use very simple mathematical dependences.

After correction of the position of the gyrostabilized platform the astronomical system of orientation will be turned off, and the system for controlling the movement of the missile corrects its trajectory in accordance with the new position of the axes of the inertial system of coordinates.

A merit of the astronomical system of orientation of a gyroplatform is its high degree of accuracy. Application of it is expedient during the launching of missiles from mobile launchers, when it is undesirable to determine oriented geodetic directions ahead of time.

CONCLUSION

A consideration of the essence of aiming and problems solved by the aiming system, makes it possible to draw a conclusion concerning the importance of aiming of ballistic missiles during preparation for launching. The nature of dispersion of points of impact of ballistic missiles depends directly on the accuracy of azimuthal aiming.

From the brief analysis of principles of construction of aiming systems of American ballistic missiles it follows that during their development a great deal of attention is allotted to automation of the basic operations of aiming. Automated systems make it possible to increase the accuracy of aiming, to reduce the number of operators servicing them, and to decrease the time for preparation of missiles for launching.

During the aiming of all American ballistic missiles oriented geodetic directions are determined ahead of time by conventional astronomical and geodetic methods or with help of ground gyroscopic devices. However, during the last few years American specialists have begun to give attention to the development of principles of aiming ballistic missiles using onboard inertial means and systems of astro-orientation. In their opinion, it is expedient to use such principles of aiming for the launching of missiles from mobile launchers.

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ABSTRACT

(U) This book is intended for soldiers, sergeants, and students in military schools, as well as for the general reader interested in missile technology. On the basis of Soviet and foreign sources the author gives an analysis of the aiming of ballistic missiles with the use of external as well as onboard information. Also presented is a discussion of gyroscopic units, tracking systems, and other information on the aiming of ballistic missiles. There is a bibliography of 14 titles.